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ABSTRACT

This report presents priorities for new facilities and new capabilities at existing facilities with initial costs of at least $5 million. The new facilities in order of priority are: (1) a 6 GeV synchrotron radiation facility; (2) an advanced steady state neutron facility; (3) a 1 to 2 GeV synchrotron radiation facility; and (4) a high intensity pulsed neutron facility. The new capabilities at existing facilities in order of priority are: (1) centers for cold neutron research, incorporating guide halls and instrumentation; (2) insertion devices on existing synchrotron radiation facilities; (3) an experimental hall and instrumentation at the Los Alamos National Laboratory pulsed neutron source; (4) upgrading of the National Magnet Laboratory; and (5) enriched pulsed neutron targets. The context of these recommended priorities is given in an executive summary, and more fully set out in the report's three chapters. Chapter I describes the nature and purpose of materials research and the status of several major research facilities in the United States and other countries. Chapter II outlines the research that has been done with existing facilities and that will be facilitated with the proposed new installations. Chapter III offers a fuller rationale for the priorities, briefly analyzes costs, and surveys facilities considered but not included in the priorities. (JN)

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Major Facilities for Materials Research and Related Disciplines

Major Materials Facilities Committee
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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Major Facilities for Materials Research and Related Disciplines

Major Materials Facilities Committee
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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Washington, DC 1984

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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NATIONAL RESEARCH COUNCIL

2101 CONSTITUTION AVENUE WASHINGTON, D. C. 20418

OFFICE OF THE CHAIRMAN

July 24, 1984

Dr. George J. Keyworth, III
Director
Office of Science and Technology
Policy
Old Executive Office Building
Washington, D.C. 20500

Dear Jay:

I am pleased to transmit a report on major materials facilities, prepared at your request by a committee of the National Research Council (NRC). As with all reports of the NRC, the report is the responsibility of its committee, but its review has been monitored by the Academies' Report Review Committee.

The report presents priorities both for new facilities and new capabilities at existing facilities with initial cost of at least $5 million. The *new facilities* in order of priority are: a 6 GeV Synchrotron Radiation Facility; an Advanced Steady State Neutron Facility; a 1 to 2 GeV Synchrotron Radiation Facility; and a High Intensity Pulsed Neutron Facility. The *new capabilities at existing facilities* in order of priority are: centers for cold neutron research, incorporating guide halls and instrumentation; insertion devices on existing synchrotron radiation facilities; an experimental hall and instrumentation at the Los Alamos National Laboratory Pulsed Neutron Source; upgrading of the National Magnet Laboratory; and enriched pulsed neutron targets.

The context for these recommended priorities is given in the executive summary, and more fully set out in the three chapters of the report proper. Chapter I titled, *Materials Research: Facilities and Modes*, describes the nature of materials research, by whom it is done, and for what purposes; and the major facilities for synchrotron radiation, neutron scattering, and high magnetic field research, in the United States

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and other countries. Chapter II titled, Major Materials Facilities: Science and Technology, outlines the research that has been done with existing facilities and that will be facilitated with the proposed new installations. Chapter III titled, Conclusions and Recommendations, offers a fuller rationale for the priorities, briefly analyzes costs, and surveys facilities considered but not included in the priorities by virtue of the Committee's charter and without necessarily passing any judgment on their relative merit.

As acknowledged in the preface to the Report, setting priorities was a "difficult and painful" task for the Committee. It should be understood that, in accordance with your request, the report did not address the question of balance between support for "small" and "big" science in materials research. The Committee hewed to its charter: to set priorities among major facilities considered important to the nation's research efforts. Therefore, the report should not be read as advocating increased support for major facilities to the detriment of smaller scale science, typically done at universities, governmental laboratories, or regional centers. Indeed, quoting from the preface, "additional panels should be convened to address other aspects of materials research and to review previous recommendations in light of new information."

With those caveats in mind, I believe this report to be a major contribution to guiding the science and technology of the United States. All of us understood that selecting priorities is a difficult task. That it was done, with care and wisdom, is due to the members of the committee, to its staff, and to the Committee's leaders, Frederick Seitz and Dean Eastman.

I commend the report to your attention.

Sincerely,

Frank

Frank Press
President

Attachment

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PREFACE

The President's Office of Science and Technology Policy in November 1983 asked the National Research Council (NRC) to assist in establishing priorities for major facilities for materials research. These facilities, defined as those with initial cost of at least $5 million, include, among others, sources of synchrotron radiation and steady state and pulsed neutrons.

A committee of twenty-two members was formed within the NRC Commission on Physical Sciences, Mathematics, and Resources, representing the diverse disciplines that use facilities for major materials. The Committee's membership was also intended to mirror the differing research styles and the spectrum of organizations where the research is done. Scientific work with materials varies from that principally requiring laboratory-scale instrumentation to that dependent on the availability of major facilities that the Committee was asked to address. It is done by governmental, academic, and industrial scientists and engineers.

The Major Materials Facilities Committee first met late in January 1984 and three times thereafter. Four panels of the Committee were formed: three to consider and make recommendations to the Committee regarding needs for synchrotron radiation, neutron scattering, and other specialized materials research facilities; and a fourth to analyze the budgetary implications of various sets of priorities. During its tenure, the Committee, or one of its panels meeting separately, was informed of or heard detailed presentations on the status and promise of many of the U.S. major materials facilities falling within its charge. Further, the President's Science Advisor, the directors of several national laboratories, and senior research officials of several federal agencies met with the Committee. [A list of presentations to the Committee is in Appendix C.] Finally, the Committee had available to it recently completed and advance drafts of reports relating to its topic, done by the National Research Council, the Department of Energy, and other organizations. In all, this report is the result of more than 6 months of extremely intensive efforts by the Committee, its panels, and its staff.

In addition to the executive summary, the report contains three chapters. Chapter I describes the facilities, research styles, and research performers of materials research in the United States. It also offers a brief summary of the status of U.S. facilities vis-a-vis those of other countries. Chapter II outlines scientific and technological accomplishments using major materials facilities and suggests the likely direction of future research. In short, it presents the scientific and technological rationale for the recommendations in this report. Chapter III expands on the conclusions and recommendations given in the executive summary.

A continuing concern throughout the Committee's deliberations was the possible misinterpretation, even misuse, of its report. As is emphasized several times in the text that follows, the knowledge generated by materials research comes from diverse research styles and performers, each vital to the total effort and each complementary to the other. These varying styles must each be well supported, for the health of the total effort in materials research. To deny funding to smaller scale research to support major facilities is destructive. Therefore, the recommendations in this report should be read and interpreted for what they are: a statement as to priorities solely for major materials facilities. The Committee did not address, and this report does not imply, any judgments on the total spectrum of work embraced by materials research.

By the same token, additional panels should be convened to address other aspects of materials research and to review previous recommendations in light of new information. Such panels, by responding to specific aspects of materials research needs, can contribute to the long-range planning and to the setting of priorities for the materials research field.

The task before the Committee was difficult and painful. Its recommendations, and its omissions, would, if they were adopted, have a major effect on the future direction of materials research in the United States, on the institutions where major facilities are or may be based, and, likely, on the future competitive status of major segments of United States technology. That the Committee fully agreed to the need to recommend priorities testifies to the cosmopolitan views of its members; that reaching agreement on priorities was difficult testifies to their strong beliefs in the value of particular facilities.

The National Research Council is indebted to the members of the Committee for their patience, goodwill, and dedication to an arduous and trying task.

Dean E. Eastman
Frederick Seitz
Co-Chairmen, Major Materials
Facilities Committee

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EXECUTIVE SUMMARY

The science of condensed matter, or materials research, deals with the properties of solids and liquids and their interfaces. It is interdisciplinary, involving materials science, major areas of physics and chemistry, and the earth sciences, biology, and medicine. The understanding of the behavior and properties of materials undergirds every major technology; as a consequence, strength in materials research is essential to national capacities in advanced technology and, hence, to economic competitiveness.

Like all sciences, materials research depends on instruments, with these instruments ranging from laboratory size, such as mass spectrometers, to major national facilities, such as sources of synchrotron radiation and neutrons.

This report deals solely with major facilities. That was the Committee's charge. The facilities considered were those that are national in scope, with initial costs on the order of $5-10 million or more, intended primarily for research on materials. However, materials research done on a laboratory scale is equally vital to the future strength of U.S. materials research. Support for laboratory-scale science is complementary to, not competitive with, the support for major facilities recommended in this report.

The relatively high costs of major facilities for materials research dictate that priorities be established; and the Committee in this report recommends priorities for major new facilities and new capabilities at existing facilities, for materials research and related fields. The recommended priorities involve three types of facilities, providing synchrotron radiation, neutrons, and high magnetic fields.

Synchrotron radiation, produced when energetic electrons are deflected by a magnetic field, provides over a broad spectral range the most intense source of photons now available. Such radiation can be intensified further by orders of magnitude by using insertion devices--wigglers and undulators--that put a series of sharp bends in the electron trajectories. Synchrotron-produced photons interact strongly with atomic electrons, thus, offering a means of probing the details of the electronic structure of materials.

In contrast, neutrons, which are produced by nuclear reactions, interact most strongly with atomic nucleii. Neutrons are thus uniquely suited to the study of lattice dynamics and molecular configurations. In addition, since the neutron has a magnetic moment, neutron scattering offers a unique means of probing the magnetic properties of materials. The most effective use cold neutrons, which have very low velocities, requires that they be transported through special tubes, whose walls reflect those neutrons with minimum loss, to large experimental areas called guide halls.

High magnetic fields are essential to the study of a variety of technical and fundamental problems. In particular, high magnetic field facilities are essential to the development of improved superconductors and, in turn, make it possible to construct more efficient superconducting magnets capable of achieving still higher fields.

The Committee applied the following criteria in establishing its priorities:

- o The importance of each facility for frontier research in materials, and consideration of research needs of other fields, including biology, chemistry, atomic and molecular physics, plasma physics, earth science, and medical science.
- o The importance of each facility for applied research in areas of national priority; that is, economic competitiveness and security.
- o The availability of other, less costly alternatives for accomplishing comparable scientific, technological, and educational goals.
- o The contribution of each facility to a long-term national plan for such facilities, including considerations such as capital investment, operations costs, and technical feasibility.

Additional criteria that should be considered in evaluating proposals for new facilities include:

- o Technical and scientific resources at the laboratory or university site, including schools or departments in related areas.
- o Access and ease of use by extramural academic, industrial, or government laboratory investigators.
- o Role of the facility relative to a new or strengthened mission of its home laboratory or university.
- o Potential of each facility for training scientists and engineers.

Further, new facilities to be fully effective must be dedicated, that is, used exclusively for synchrotron radiation or neutron based research. Finally, to serve the entire community optimally, the geographic distribution of facilities should generally be taken into account.

CONCLUSIONS AND RECOMMENDATIONS

The Committee's recommended priorities for major facilities--both new facilities and new capabilities at existing ones--embody two prerequisites:

- That they are accompanied by expanded support of smaller materials research programs, including related instrumentation. Research on this scale continues to provide much of the fundamental new science in the field and to train a large fraction of our scientific and technical manpower.

- That resources must be provided to operate existing user facilities productively. In addition, the approved enhancements of major synchrotron radiation facilities at the Brookhaven National Laboratory, Stanford University, and the University of Wisconsin should be completed expeditiously, since it will require several years to more than a decade before the new facilities recommended in this report can contribute to the research effort of the United States.

RECOMMENDED PRIORITIES

The Committee's recommended priorities for the development and construction of facilities during the next decade include two categories:

- Major new facilities, and

- New capabilities at existing facilities.

These categories complement one another in function, time scale, and required resources. New capabilities at existing facilities are essential for scientific and technological needs in the next decade, while the long lead times needed to construct major new synchrotron radiation and neutron facilities require that we start now with the planning and design of such new facilities. They also require that we begin immediately to implement new capabilities at existing facilities. The Committee concludes that both categories are essential for the effective evolution of science and advanced technology in the United States in the next decade and beyond.

The Committee also recommends the convening of additional panels to address other important aspects of materials research.

Major New Facilities

The Committee's recommendations for the construction of major new facilities are listed below in order of priority.

1. A 6 GeV Synchrotron Radiation Facility. This would be designed to make optimum use of the new scientific and technological opportunities presented by insertion devices. These devices, by providing radiation having orders of magnitude greater brightness than currently available, will make it possible to expand on the seminal research using synchrotron radiation carried out in the past decade. A synchrotron radiation facility with a storage ring energy of about 6 GeV will offer both identifiable and unforseeable new opportunities for research throughout the electromagnetic spectrum. It is optimal for providing radiation from undulators at about 10 keV, where most x-ray research is done. For example, the brightness increase will make it possible to investigate the properties of more complex materials and smaller samples with increased spatial and energy resolution. Site-independent design should begin immediately, and the site selection and construction should commence as soon as possible. If construction were to begin, for example, in FY 87, operation is possible by FY 92.

2. An Advanced Steady State Neutron Facility. The goal is to achieve about ten times the flux of existing machines with a minimum requirement of five times the flux. There are two principal reasons for this recommendation. First, and most important, a high-flux source can be designed to optimize beam geometry and flux distribution, so as to yield greatly increased intensities for all experiments. An increase of about ten times the flux of existing machines is an aggressive but technologically feasible goal. Such a facility would ensure the United States a leading position in this field. This is especially important in the cold neutron range, where flux increases of an order of magnitude can be achieved, providing new capability, for example, for high-resolution spectroscopy and small-angle scattering studies. Second, a new source will be a timely replacement for one or more of our existing sources built in the 1960's. Site-independent design should begin immediately. However, because of safety requirements, the Committee does not expect construction to begin until about FY 89 with completion possibly by FY 96.

3. A 1 to 2 GeV Synchrotron Radiation Facility. This facility would be centered around insertion devices but optimized for the vacuum ultraviolet (VUV) and soft x-ray region. This facility furnishes additional scientific and technical opportunities for research in chemical physics, electron spectroscopy, and imaging techniques such as microscopy and holography.

4. A High-Intensity Pulsed Neutron Facility. Pulsed neutron sources offer new scientific capabilities, especially for investigations requiring higher energy, or greater than thermal, neutrons. Also, there are practical limits to the intensity that steady state reactors can provide. Thus, future improvements in neutron sources, beyond the second priority above, will probably come from alternative approaches, the most promising of which is based on pulsed neutron

sources. However, future action on the construction of a high-intensity pulsed source (about 10^{17} neutrons/cm^2-sec peak flux) should be based upon the results obtained with lower-intensity pulsed sources.

New Capabilities at Existing Facilities

Recent developments make it both practical and cost effective to adapt certain existing user facilities to new purposes by adding experimental halls, instruments, and modified sources. These additions provide an opportunity for new frontier science; they are not simply extensions of existing work.

The Committee's recommendations in order of priority for the addition of these new capabilities at existing user facilities are:

1. Centers for Cold Neutron Research. Guide halls and instrumentation for exploiting the only cold neutron sources in the U.S. located at the Brookhaven National Laboratory and at the National Bureau of Standards, should be developed in an orderly fashion.

There is no cold neutron guide hall in the United States, and such facilities are urgently needed to address the rapid expansion of neutron applications in materials science, chemistry, and biology. Many central problems in these sciences can only be solved using new instruments with cold neutron beams. These centers will enable U.S. scientists to be competitive in cold neutron research during the next decade; and they will provide new instrumentation concepts for developing future neutron scattering sources.

2. Insertion Devices on Existing Synchrotron Radiation Facilities. Insertion devices should be developed in an orderly fashion to exploit about six of the remaining straight sections of existing storage rings. The special characteristics of undulators as radiation sources should be emphasized, to use our existing capability most effectively.

Undulators on existing machines will be our premier synchrotron radiation source for the next 5 years. They will also provide valuable experience for the next generation of synchrotron radiation facilities which will also be based upon undulators. The construction of additional insertion devices, when approved, should follow the construction of new capabilities at synchrotron radiation facilities already included in the budgets for FY 85 and FY 86.

3. Experimental Hall and Instrumentation at the Los Alamos National Laboratory. An experimental hall and new instruments at the pulsed neutron source at the Los Alamos National Laboratory (LANL) would make the United States competitive in pulsed neutron research and would help guide the development of future pulsed sources.

The expected flux increase at this facility is an important opportunity to explore, at modest cost, the great promise of pulsed neutron science for spectroscopic and structural problems.

4. Upgrading of the National Magnet Laboratory. The need for timely development of pulsed magnetic field facilities and instrumentation enhancements at the National Magnet Laboratory has been demonstrated. This laboratory, the only major high magnetic field research facility in the United States provides a unique combination of high fields and low temperatures. Many advances in research depend on its continued development as a dedicated user facility.

5. Enriched Pulsed Neutron Targets. Enriched targets, by exploiting fission events to amplify the neutron flux, can more than double the available flux. The development and installation of enriched targets for use at pulsed neutron facilities would be cost effective.

Priorities 1 and 2 for major new facilities, when they are implemented, would serve as a centerpiece of this nation's future capability for synchrotron radiation and neutron based research. Thus, design and siting studies for a 6 GeV synchrotron radiation facility and for an advanced steady state neutron facility should begin immediately.

Because of the long lead time associated with an advanced steady state neutron facility, the immediate implementation of at least one instrumented cold neutron guide hall is necessary to provide forefront capability.

The basis for these conclusions is expanded upon in the body of the report. Chapter I outlines the characteristics of materials research at universities, at governmental and private laboratories, and in industry, including research styles, research organizational modes, instrumentation, and the role of national facilities. It also offers a brief summary of the status of U.S. facilities vis-a-vis those of other countries. Chapter II outlines scientific and technological accomplishments, using major materials facilities, and suggests the likely direction of future research. It presents the scientific and technological rationale for the recommendations in this report. The Committee's conclusions and recommended priorities for national facilities for materials research and related fields are given in Chapter III.

The Committee again emphasizes that, in response to its charge, its recommended priorities include only synchrotron radiation, neutron scattering, and high magnetic field facilities. Other meritorious materials research facilities were also discussed by the Committee. A number of these are briefly described in Chapters I and III.

I. MATERIALS RESEARCH: FACILITIES AND MODES

Materials research is by its nature interdisciplinary, historically calling on expertise from engineering, physics, earth sciences, and chemistry and, recently, extending to biology and medicine.

In this chapter, we briefly describe the diverse research styles and types of facilities, instrumentation requirements, organizations, and modes of materials research. This is intended to set the context for the focus of the report: major neutron, synchrotron radiation, and high magnetic field facilities, costing in excess of about $5 million. These are all are national user facilities, each serving a group or groups of users whose interests often extend beyond the traditional materials research community. This focus responds to the charge to the committee, as stated in the opening sentences of the Preface and the Executive Summary.

Universities, the federal government, and private corporations are all involved in materials research. In universities, it is done in the main in different disciplinary departments. Within the government, it is done within facilities operated for the U.S. Department of Energy by private contractors, such as the Oak Ridge National Laboratory, the in-house laboratories of the Department of Defense, such as the Naval Research Laboratory, and other laboratories such as the National Bureau of Standards. Numerous industrial laboratories are also involved in materials research, usually in an interdisciplinary mode, ranging in focus from fundamental work to development and manufacturing.

UNIVERSITIES

Much of the materials research in the United States is done in small university laboratories, consisting of a few researchers and a total instrumentation inventory of less than $1 million. Research on this scale continues to provide important, fundamental new science and to train a large fraction of our scientific and technical manpower.

Universities have a crucial role in materials research. They are a major source of new ideas and concepts that often take years to mature, time that industry often cannot commit. And they are the sole source of future materials scientists and engineers. Universities also operate special research facilities that are used by a broader research community.

Training new scientists and engineers for materials research is complicated by the needs of advanced technology for people who are broadly trained and fully conversant across the conventional disciplinary boundaries, such as, for example, condensed-matter physics and chemical engineering.

An important task for the universities is to develop stronger ties with industrial and governmental laboratories. Such cooperative programs stimulate new research, promote the exchange of new knowledge and technology, and help in thecontinuing education of mature technical personnel at industrial and governmental laboratories.

Materials Research Laboratories

The Materials Research Laboratory (MRL) program, supported by the National Science Foundation and the Department of Energy, is intended to stimulate interdisciplinary materials research within universities, of the sort not easily done under the traditional funding pattern of individual research projects. It emphasizes coherent, multi-investigator projects requiring collaboration among individuals in two or more materials-related disciplines. The MRL program has also emphasized the development of wellstaffed and well-equipped central research facilities, partly as mechanisms for stimulating collaboration. Finally, new projects can be quickly started with MRL funding including seed funds to assist both new faculty members and established faculty members with novel ideas or programs who wish to change research fields. MRL core support is not intended as a substitute for individual research project funding, but may properly catalyze significant new research initiatives. Several Materials Research Centers at universities are funded by the Department of Energy and by other agencies. A smaller kind of specialized program, the Materials Research Group, is currently under consideration by NSF.

Instrumentation for Materials Research*

The status of instrumentation in university research laboratories was examined in a 1971 study of the National Research Council (reference 23), commissioned by the National Science Foundation. At that time, a need for $200 million in new instrumentation was identified. Only a small fraction of the need was met at the time, leading to a more problematical situation now. Thus, in the intervening decade, the consumer price index rose by slightly more than a factor of three, while instrumentation costs inflated at almost twice that rate. The accumulated need is now at least $1 billion, and some estimates are considerably higher. The $1 billion estimate is what would be needed to bring university research laboratories up to modern standards and does not include the cost of major new facilities, such as reactors or accelerators. Results from a 1984 National Science Foundation instrumentation survey (reference 24) indicate that only 16 percent of current academic research equipment in the physical sciences could be characterized as "state of the art." Dealing with this crisis in university instrumentation is a matter of national urgency.

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* While this discussion of instrumentation focuses on the needs of the universities, many of the same problems are faced by governmental laboratories engaged in materials research.

Small- and Large-Scale Instrumentation. Exacerbating the shortcomings in university instrumentation is the increasing need for new larger-scale instrumentation for small research groups, instrumentation that is expensive by traditional standards but modest by those of the national facilities. In some cases, the cost of such instrumentation, typically $250,000 to $1,000,000, will necessitate considerable sharing, usually with other investigators or groups at the same institution. Examples include electron microscopes, the new generations of high-powered or very fast lasers, equipment for studying specialized materials, such as molecular beam epitaxy or chemical vapor deposition apparatus, specialized environments such as "clean rooms," very high powered or pulsed magnets, and dedicated 32-bit superminicomputers.

The cost of equipping many experimental stations at large user laboratories is also in this category. For example, most of the beam lines at existing synchrotron radiation facilities now are financed by participating research teams from governmental, industry, and university laboratories. These groups provide their own funding for instrumenting ports to do particular kinds of experiments. It is expected that about half of the additional beam lines proposed in this report for the new and enhanced synchrotron radiation facilities will be funded by the research participants. Future neutron facilities may also be partly developed in this mode.

Large-Scale Computers. Over the past decade, a new and essentially different kind of instrument has been added to the increasingly complex instruments for experimental materials science: the large-scale computer, or supercomputer. Although simple properties of simple systems, such as the cohesive energies of elemental solids, can be calculated within about 10 hours with a 32-bit superminicomputer, calculations for more complex and interesting systems require vastly larger memory and increased computing speed. Greatly increased computing support, during the next 5 to 10 years, would qualitatively affect the usefulness of theory for the solution of materials problems.

Personnel

The need to fully use the facilities discussed here, coupled with the generally complex nature of modern materials research, implies a much more extensive use of technical and professional support staff in individual research groups than has been customary in the chemistry, physics, and materials science communities in universities. Biological scientists in universities are now well established in this mode of operation, as are many physical scientists in industrial and governmental laboratories.

FEDERAL LABORATORIES

The federally supported laboratories have widely diverse roles in U.S. materials science and technology, in keeping with the missions of their agencies. Thus, the national laboratories of the U.S. Department of Energy (DOE) conduct materials research related to the development of nuclear fission, fusion, and other energy sources, as well as to weapons. As do other federally supported laboratories, the DOE laboratories also operate special research facilities that are widely used by the broader scientific community. In fact, the special scientific or measurement capabilities, as well as the major facilities, of the federal laboratories, are the basis for their many cooperative research efforts with industry and universities.

The materials research and development activities of the laboratories of the Department of Defense (DOD) directly support general defense needs or particular weapon systems. Fundamental work in materials research centers on those activities areas inadequately addressed by the private sector or activities that may have an important long-range impact on the scientific or technological needs of future defense capabilities. Overall, the DOD laboratories can engage, when it is necessary, in all aspects of materials research and development, from fundamental concepts to providing prototypes. Finally, the direct role of the DOD in materials research is complemented by its indirect role in broadly supporting contract R&D at academic, industrial, and governmental laboratories of other agencies.

Other governmental departments and agencies also have major roles in materials research. For example, one of the central missions of the National Bureau of Standards, within the Department of Commerce, is research leading to new or improved measurement methods and standards and to basic understanding of the properties of materials needed by industry, universities, and government. The U.S. Geological Survey, within the Department of the Interior, has a major effort in basic and applied materials research related to the nation's mineral resources.

INDUSTRY

Condensed matter science is unusual in that a significant portion of basic research in the U.S. is performed in industry. This reflects the fact that condensed matter science supports advanced technologies in many areas of national priority, including those of information systems, energy, health, transportation, and national security. Basic industrial research is conducted in all sub-areas of condensed matter science using many modes, ranging from the individual researcher to research groups. Industrial researchers also make active use of national facilities and collaborate in these efforts with university and governmental researchers. Multidisciplinary materials research is often carried out effectively at the major U.S. industrial research laboratories.

In addition to playing a major role in basic materials research, industry also helps define the future materials needed to advance important key technologies. That, in turn, serves as a guide to research at university and governmental laboratories as well as at industry laboratories.

The largest materials research effort in the U.S. undoubtedly is the industrial research and development effort focused upon product lines. Because this effort often requires advanced applications of materials for specialized uses, it generally requires a fundamental understanding of materials. The availability of university-trained scientific and technical personnel is essential for this extensive industrial research and development. Collaboration by industry researchers, with scientists and engineers at both university and governmental laboratories, contributes substantially to technology transfer. Recently, specialized facilities, such as microelectronics-related facilities, have been created at universities to address both basic research and the technology needs in industry.

MAJOR MATERIALS FACILITIES

Within the above perspectives on the diversity and range of facilities and practioners of materials research, the Committee describes below the status of several major materials facilities in the United States. These facilities are more fully described in a recent review article (reference 22).

Synchrotron Radiation Facilities

The synchrotron radiation facilities in the United States today range from small, virtually in-house facilities to large user facilities. The Cornell High Energy Synchrotron Source (CHESS) is a laboratory using a 5.5 GeV storage ring parasitically. The six end stations serve about 250 users annually. The National Synchrotron Light Source (NSLS) at the Brookhaven National Laboratory has two storage rings, 0.75 and 2.5 GeV, dedicated to the use of synchrotron radiation. Approximately 58 end stations, including those in a current upgrade program, serve a growing user community, currently estimated at 400 scientists annually. The Synchrotron Radiation Center (SRC) at the University of Wisconsin, currently operates a 0.24 GeV storage ring and is commissioning a 0.75 to 1.0 GeV ring. The 20 beam lines on the latter serve an estimated 150 users annually. The Stanford Synchrotron Research Laboratory (SSRL), at the Stanford Linear Accelerator Center, uses a 3.5 GeV storage ring dedicated to synchrotron radiation part of the year and in a parasitic mode the rest of the year. Counting beam lines in a current upgrade program, the 19 end stations serve a user community of 300 scientists. In addition, one undulator beam line is to be built on a 15 GeV storage ring at the same site.

The Synchrotron Ultraviolet Radiation Facility (SURF), at the National Bureau of Standards, is a 0.24 GeV ring dedicated to synchrotron radiation use. Its 13 beam lines serve about 40 users annually. Expanded descriptions of these facilities and a definition and history of the user community, as well as its characteristics, can be found in two previous reports (references 5, 8).

Of the storage rings listed above, only three--two at NSLS and one at SRC—were designed to be sources of synchrotron radiation, and those three were all designed prior to a full recognition of the importance of insertion devices. Consequently, they were designed to emphasize the radiation from the bending magnets, with capabilities for the later addition of a limited number of insertion devices. (For a description of insertion devices, see Chapter II and references 5, 8, 18, 19, 20, 26.)

Foreign Synchrotron Radiation Facilities. Many synchrotron radiation facilities exist elsewhere, offering strong competition to U.S. scientists. These are extensively described in other reports (references 5, 8). The principal operating sources are in England (SRS), France (ACO, super ACO), West Germany (HASYLAB, BESSY), Japan (Photon Factory), and the USSR (VEPP-3, VEPP-4). There are other facilities in some of these countries, as well as in Italy and Sweden. Construction is under way for facilities in the People's Republic of China, and there are plans for facilities in Taiwan, India, and Brazil. None of the facilities mentioned above is more advanced than our newest facilities, NSLS and SRC. However, the European Science Foundation is planning to build a 5 to 6 GeV storage ring very similar to that proposed for the United States.

Neutron Scattering Facilities

There are, currently, active neutron scattering programs at five different national centers: Argonne (ANL), Brookhaven (BNL), Los Alamos (LANL), National Bureau of Standards (NBS), and Oak Ridge (ORNL). The BNL, NBS, and ORNL facilities center around steady state reactor sources, while ANL and LANL involve pulsed spallation sources. There are also reactor based neutron scattering programs at the University of Missouri, the Massachusetts Institute of Technology, and other universities. This section focuses on the national centers for neutron research.

The BNL facility centers around the 60 MW High Flux Beam Reactor (HFBR), which has a thermal flux of 1×10^{15} neutrons/cm^2-sec. It is equipped with eleven spectrometers and diffractometers, with two more under development. The NBS facility has nine end stations, with a tenth under development. A cold source has been installed on the BNL reactor, and funding has been provided for installation of a large volume cold source in the NBS reactor. The ORNL facility centers around the 100 MW High Flux Isotope Reactor (HFIR), which has a thermal flux of 1×10^{15} neutrons/cm^2-sec. It is equipped with nine scattering instruments, with a tenth under development. The instruments include a 30-meter small-angle scattering instrument that is funded by NSF as a national user facility. The ANL facility centers around a pulsed neutron source that produces bursts of neutrons with a peak thermal flux of 4×10^{14} neutrons/cm^2-sec at a 30 Hz repetition rate. It is now the most intense pulsed source in the world, equipped with eight instruments, with a cold moderator available for several beams. The LANL facility centers around a pulsed spallation source that, by 1986, will provide a peak thermal flux of about 1×10^{16} neutrons/cm^2-sec at 10 Hz. Six beam lines are now available, with two instruments operating in the user mode. Ten or more beam lines will ultimately be developed.

All of these centers have ancillary equipment, enabling one to study samples in varied environments with temperatures from 0.3K to 1800K, pressures up to 20 kbar, and magnetic fields up to 80 kG. There is extensive research by outside users at each center, with the individual center user programs varying from informal collaborations to a formal peer-reviewed process. In most cases, outside user experiments involve collaboration with in-house people.

Aside from the facilities described above, there are efforts at the various neutron centers to develop area detectors, multilayer polarizing monochromators, focusing collimators, and neutron choppers and polarizers, all of which are important for developing advanced instrumentation for reactor or pulsed sources. These efforts, in general, have a low-to-modest level of support and manpower compared with instrumentation projects in Europe, discussed below.

Foreign Neutron Scattering Facilities. This subsection offers a selective review of foreign neutron scattering facilities, concentrating on instrumentation developments particularly in Western Europe that have not been matched in the United States. An important key to the European success, especially at the Institut Laue Langevin (ILL), has been the development and use of cold neutron sources and associated guide halls to create instruments for ultra high-resolution and high-sensitivity spectroscopy. These currently provide energy resolutions as much as five orders of magnitude better than those available in the United States; they also enable studies of small-angle and medium-resolution diffraction and other new scientific applications. As already noted, there is only one cold neutron reactor source in the United States, at BNL, and another under development, at NBS.

The United States has no guide halls to improve the versatility and flexibility of cold or thermal neutron instruments. In contrast, 60 percent of the neutron scattering instruments at the ILL (reference 7) are located in a large guide hall, and a new guide hall and cold source are to be completed over the next 2 years. Also, there are major efforts at ILL to develop and construct focusing monochromators, polarizing devices, reflecting supermirrors, environmental control systems, dedicated instruments for diffraction surveys using neutron cameras, and more. Besides the ILL program, there is a new reactor center, called Orphee, at Saclay near Paris, with two hydrogen cold sources, which will ultimately commission over twenty new instruments for neutron scattering and fundamental physics research. Expanded guide halls with many new instruments are also under construction at the KFA Research Reactor in Julich and at the Berlin reactor. Finally, the Japanese government has approved funding for the complete modernization of the JAERI III Reactor at a cost of $150 million, including a replacement of the vessel, an upgraded fuel and beam tube arrangement, and installation of a large cold source and guide hall.

The total current operating expenditures for neutron scattering at research reactors in Western Europe is about $80 million per year, in FY 83 dollars, including associated reactor operation costs, roughly triple the U.S. effort. An order of magnitude difference emerges when one compares capital investment for new spectrometer development and construction efforts. The consequences of this investment gap over the past decade between European and U.S. research reactors are being felt increasingly in our inability to compete in many areas of new science involving such techniques as high-resolution neutron spectroscopy, small- and medium-angle diffraction, and diffuse scattering.

The current U.S. position in pulsed neutron research and development is better in relative terms with respect to foreign competitors than for steady state sources. For example, the Intense Pulsed Neutron Source (IPNS) at Argonne is presently the highest intensity facility in the world, and the Weapons Neutron Research/Proton Storage Ring (WNR/PSR) at Los Alamos is scheduled to provide, by 1987, an order of magnitude increase in intensity for pulsed neutron experiments.

However, developments abroad make current comparisons misleading. For example, the SNS advanced spallation source under construction at the Rutherford Laboratory in Britain, which is scheduled to be brought on line by the end of 1984, will have neutron intensities 2 to 3 times the current IPNS performance and will, by 1986, generate a peak thermal flux of 5 x 10^{15} neutrons/cm^2-sec at a 50 Hz repetition rate. That is roughly twice the total intensity of the scheduled WNR/PSR source. This facility will ultimately have a complement of at least 15 neutron scattering instruments. Moreover, the Japanese, who have developed a modest flux facility at Tsukuba with an impressive array of instruments, are also funding a planning and design study for a major new pulsed source, costing $100 million in FY 83 dollars, which would slightly exceed the characteristics of the SNS at the Rutherford Laboratory.

User Policy at Major Materials Facilities

Since major materials facilities are intended for a large community of scientists, it is very important that they be available to all qualified research investigators with meritorious proposals. A number of approaches have been used in the past to arrange participation, each having strengths and weaknesses. Some perspectives and generalizations from experiences to date are given below to help guide the formulation of future policies.

Criteria. There are several extant models of user policies for major neutron and synchrotron radiation facilities. In general, they satisfy the following generic criteria:

1. Experimental activities, except for construction and maintenance, whether they are initiated by research staff of the facility or by outside scientists, are presented and justified in written form. The proposals are reviewed before research is authorized and begun.
2. Committees reviewing proposals include a substantial fraction of scientists from outside the facility.
3. Priorities are established by the facility director based on ratings of the review committee and on scheduling considerations. The director has the discretion to provide for the insertion of experiments to exploit blocks of instrument time that are freed by unanticipated events.
4. Use of a facility is not restricted to U.S. scientists, but priority may be given to them in the event of equivalent proposals.
5. The time assigned for an experiment is designed to be adequate for the measurements, but extensive, repetitive, or confirmatory measurements may require the submission of additional proposals.
6. Some fraction of instrument time should be made available for use by the director at his or her discretion. This time can be used to extend assigned periods for current experiments, to permit preliminary experimentation in advance of a proposal, and for instrument development. Approximately 20 percent of instrument time is suggested for such purposes.
7. Users should be provided with an adequate level of technical support at the instrument so that they can safely and efficiently conduct experiments. Vacuum interlocks, shielding, and other safety devices should be controlled by facility management. The design of user facilities should make it impossible or difficult for any user at one port to affect the beam delivered to any other port.
8. The facility should provide a stock of standard test instruments, normal electronic and vacuum components, cryogenic fluids (liquid nitrogen and helium), data acquisition computer systems, commonly used gases, and some minimum storage space for user owned equipment.
9. It should be recognized that there are a range of user interactions. Some users will make very short-term and straightforward measurements, others will do long-term, interactive experiments in

which protocols and parameters are altered as the experiment proceeds. The different needs of these groups should be considered in designing facility user policy.

Participating Research Teams. A concept that has been used successfully in several major facilities is that of the participating research team, or PRT. This is a group of individuals who take communal responsibility for the design, construction, and operation of an instrument at an existing port. The PRT may also be responsible for organizing funding for the instrument. Industrial, university, and governmental groups have formed PRT's. It is a concept that appears to provide a reasonably successful approach to using facilities.

The principle is that, for a specified period--2 to 3 years, for example--the PRT has some 75 percent of the running time for that port, outsiders being allocated 25 percent. This has the advantage that the management of each instrument becomes much more flexible for members of the PRT, and more effective science may therefore be done. An important responsibility of the PRT's is to provide help for outside users. By augmenting the local staff in this manner, the entry barrier for naive users can be reduced. In some cases, PRT's are reviewed every 3 years for possible renewal; involvement with outside users is an important consideration in such renewals. A PRT is responsible for maintaining the instrument. If the PRT does not find its own outside users through collaborations, the facility director can assign an outsider to use the PRT's line during the open time.

Maximal use of a facility may involve a mixed mode operation in which some beam lines are operated by PRT's and some by the facility. The consequent flexibility of operation at the scientific level justifies the administrative complexity of such an arrangement.

Whatever the user policy, the experience to date indicates that it is important to keep the level of bureaucracy as low as possible, even if there is some loss of efficiency in using the instrumentation. This criterion tends to conflict with that of extensive peer review of lengthy proposals by potential users, so some balance is called for.

A mixed mode operation in which a facility has participating research teams and provides instruments seems an appropriate balance. It is not the intent of the Committee to spell out a rigid user policy for future major materials facilities. Any proposals for a new facility, however, should include a well-considered plan for utilization, taking into account the considerations mentioned above. The aim, of course, is to create user policies that permit the best science in an atmosphere of equal opportunity for different users.

II. MAJOR MATERIALS FACILITIES: SCIENCE AND TECHNOLOGY

Condensed-matter science, or materials research, deals with the diverse properties of solids and liquids and their interfaces. It is interdisciplinary, involving materials science, including metallurgy, ceramics, polymers; major subareas of physics and chemistry; as well as the earth sciences, biology, and medicine. Interest in materials research derives from fundamental science and technology. It is an intellectually stimulating area of science, as shown by the discoveries of fundamentally new phenomena, concepts, and states of matter during the past decade. Indeed, several recent Nobel prizes have been awarded for research in condensed-matter science.

Condensed-matter science supports advanced technologies in areas of national priority, including those of information systems, communication and computers, energy, health, transportation, and national security. Products of condensed-matter science, such as the transistor and the integrated circuit chip, have revolutionized our lives through their use in television, calculators, electronic watches, personal computers, appliances, autos, and innumerable other applications. In Table II.1, the Committee summarizes the connection between subareas of materials research using major facilities and technological applications.

SYNCHROTRON RADIATION, NEUTRON SCATTERING, AND MAGNETIC FIELDS

The spectroscopic analysis of matter involves bombardment with particles, such as neutrons or photons, with or without energy changes, or the use of high magnetic fields. The sensitivity that can be achieved is limited by the intensity of the radiation or the strength of the field.

Neutrons

The neutron is a unique probe that interacts weakly with atomic nuclei. The magnetic moment of the neutron makes it especially suited for examining magnetic properties of materials. By measuring changes in the

Table II.1. Connection Between Materials Research Subareas and Other Fields that Utilize Major Materials Facilities and Technological Applications of National Interest

	Information Systems (computers, communications, electronics)	Energy (fossil, nuclear, fusion, solar,...)	Health (Medical, Biotechnology, Environmental)	National Security	Transportation (ground, air, space)
Semiconductors	+	+	+	+	+
Metals and alloys	+	+	+	+	+
Insulators	+	+		+	+
Polymers	+	+	+	+	+
Ceramics	+	+		+	+
Magnetic Materials	+	+	+	+	+
Catalysts		+	+	+	+
Adsorbates		+	+	+	+
Lamellar (layered) materials	+	+		+	+
Composites		+	+	+	+
Biological molecules, macromolecules, and membranes			+		
Gaseous molecules and atoms	+	+	+	+	+
Plasmas (atoms, ions)		+	+	+	

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* In addition to bulk materials, thin films, interfaces, and surfaces of several of the above materials are of major scientific and technological importance.

momentum and energy of neutrons scattered by matter, direct information can be obtained on the structure of matter as well as its states of excitation.

For example, neutrons slowed to relatively low velocities--"cold neutrons"--have been used to "look" at the shapes of molten polymers. The technique is based on the fact that hydrogen and its heavier isotope, deuterium, scatter neutrons differently. Polymers are prepared in which hydrogen atoms are replaced by deuterium; isotope substitution does not alter the molecular configuration. Thus, when two polymers--ordinary and deuterated--are then exposed to a beam of cold neutrons, the actual size and configuration of the polymer can be deduced by comparing the different forms of neutron scattering from the two polymers.

Increased emphasis on research using cold neutrons is dependent on the availability of "guide halls," which are large experimental areas in which high resolution neutron spectrometers can be placed. This is possible because of the development of "guide tubes," which allow the neutrons to be transported many meters to the guide hall without significant loss of intensity.

Neutron beams can be either continuous or pulsed. Continuous beams are obtained from nuclear reactors, using controlled nuclear fission of uranium surrounded by suitable neutron moderators and reflectors, such as D_2 and beryllium. Pulsed neutron beams are generally produced from short bursts of high energy protons or electrons from an accelerator impinging on a heavy metal target, such as uranium or tungsten, to generate bursts of very high energy neutrons. This target is surrounded by a moderator-reflector assembly that is analogous to, but generally smaller than, that in a reactor, so that relatively short bursts of thermal and fast neutrons are produced at rates of 10 to 100 pulses per second.

Synchrotron Radiation

Synchrotron radiation is a unique source of photons, by virtue of its high intensity, brightness, stability, and broad energy range, extending from the far infrared to the x-ray region and beyond. It is created when charged particles within an electron accelerator are deflected by a magnetic field. The intensity of the synchrotron radiation can be further increased with the use of insertion devices. The simplest of these is the wiggler magnet that puts a relatively sharp kink in the electron trajectory of the synchrotron, thus increasing the radiation from that point. A more sophisticated device called an undulator in effect puts in a series of kinks so arranged that the light from each adds up in phase, giving an enormous increase in the intensity that can be achieved. Although synchrotron radiation represents a drain of energy in an accelerator, it was eventually recognized to be a source of intense radiation for new classes of experiments, first in solid state physics and then in other sciences.

Measurement of the momenta and energy of synchrotron-produced photons, which interact strongly with electrons, provides information on structure and excitations. Such excitations range from molecular vibrations, measured in the infrared, to the ejection of electrons from the innermost electron shells of atoms by photons in the x-ray region of the spectrum.

Such capabilities are very important for many fields. For example, synchrotron radiation is a major tool in probing the geometry and electronic structures of surface and solid-solid interfaces. In particular, photons from synchrotron radiation are used for photoelectron spectroscopy, in which electrons are ejected and their energy and angular distribution then measured.

Magnetic Fields

High magnetic field research is important for the fundamental understanding of a broad range of materials properties. Scientific advances in such diverse areas as superconductivity, permanent magnet research, and semiconductor science, all benefit from research based on the availability of intense magnetic fields. The attainment of such fields is ultimately connected to useful applications, development and industrial commercialization. Each time a higher magnetic field strength is achieved, it is quickly exploited by the scientific community and is accompanied by a requirement for yet higher field strengths. This new demand often requires a combination of high fields and low temperatures, or the combination of high magnetic fields with ancillary measuring equipment such as precision optical systems.

Superconductivity is the research area most strongly linked to high magnetic fields. An understanding of superconductors, which could form the basis for new and improved high field magnets, depends upon experiments carried out in some of the highest available fields. Therefore, the availability of present-day high field facilities is closely linked to the development of future facilities. High magnetic fields are also essential for probing those fundamental properties of superconductors that can be used to test microscopic theories, including theories based on the concept of electron pairing.

Basic Principles And New Problems

Against this background, it should be recognized that a family of basic principles and techniques underpins the field of materials research. Some of these have already been well exploited and are well understood. For example, the existence of lattice vibrations of short wavelength in metals was settled decisively with the use of neutrons some 25 years ago. Likewise, the electron energy band dispersions of solids and surfaces have been determined directly using photoelectron spectroscopy. Extended X-Ray Absorption Fine Structure (EXAFS) has been employed extensively to determine site-specific atomic structure for parts-per-million impurity concentrations and adsorbates. However, the applications of x-ray and neutron scattering to biology and polymer science, as well as to other aspects of materials science, are just beginning.

Effective, increased use of such techniques for improved understanding of fundamental biological processes will require the establishment of additional mechanisms for bridging between physical and biomedical scientists.

As theoretical concepts and processes for synthesizing materials advance, new problems come to the fore. Many involve the acquisition of detailed information regarding structural and dynamic properties that can be provided with the techniques employing neutron scattering, synchrotron radiation, or strong magnetic fields. Although it is impossible to forecast exactly how these techniques will be used to solve such problems, the Committee can predict confidently that there will be new problems a decade from now that will be especially amenable to approach with the equipment available at major materials facilities. The value of having equipment with advanced capabilities available to solve as yet barely discernible problems should not be underestimated. To indicate the breadth of applicability of such facilities, a partial list of available techniques is summarized in Table II.2.

Many problems that are well defined now cannot be explored adequately because the appropriate instrumentation or facilities are not available in the United States. Examples include the determination of the dynamics of intercalate species in single crystals of intercalated graphite having semiconducting properties. This problem can be approached using neutron scattering, along with nondestructive determinations of the concentration of electronic impurities in the range of 0.1 ppm using an x-ray microprobe.

In the following sections we discuss areas of science in which new major materials facilities can be expected to make further important contributions. More extensive summaries are described elsewhere (references 1, 2, 5, 7, 8, 18, 20).

SYNCHROTRON RADIATION RESEARCH: PAST AND FUTURE

Research with synchrotron radiation began in the 1960's and has grown dramatically in the past decade. Whenever a synchrotron radiation facility offering an increase in brightness, typically by a factor of from 10 to 10,000, became available, new types of research became possible. Furthermore, experiments carried out with such new equipment have usually demonstrated how new science could be developed if still higher brightness was available.

Four Generations

We have gone through three generations of such increases in brightness; the fourth is at hand. The first was associated with synchrotron radiation from the bending magnets of storage rings built for particle or nuclear physics. The second came with the construction of new storage rings specifically intended to produce synchrotron radiation (reference 1). These are now in operation or soon will be. The third emerged with the realization that insertion devices, wigglers and undulators

TABLE II.2. Techniques Available at Synchrotron Radiation and Neutron Facilities

		Photons	
	Neutrons	X-ray	Soft X-ray and VUV
I. Elastic scattering*			
Bulk crystallography	x	x	
Surface crystallography	x	x	
Molecular cystallography	x	x	
Small angle scattering	x	x	
Polarized scattering	x		
Magnetic scattering	x		
Diffuse scattering	x	x	
II. Quasielastic scattering			
Diffusion	x		
Reorientation	x		
Critical dynamics	x		
III. Spectroscopy and elemental analysis			
Inelastic (E,k) scattering			
- electrons		x	x
- phonons	x		
- magnons	x		
Absorption, reflection, fluorescence		x	x
Absorption spectroscopy			
- EXAFS		x	x
- SEXAFS		x	x
- PHD		x	x
Photoelectron spectroscopy			
- core level		x	x
- valence level		x	x
- ARPES		x	x
- yield spectroscopy		x	x
Photon stimulated desorption			x
Photo chemistry		x	x
Activation analysis			
- thermal neutron activation	x		
- prompt γ-ray	x		
- fast neutron activation	x		
- nuclear track	x		
IV. Imaging and microscopy			
Microscopy			x
Microprobe		x	x
Depth profiling	x	x	
Topography	x	x	

TABLE II.2 (continued)

			Photons	
		Neutrons	X-ray	Soft X-ray and VUV
IV.	Imaging and microscopy (continued)			
	Lithography			x
	Interferometry	x	x	
	Radiography	x	x	
	Autoradiography	x		
	Holography			x
V.	Radiation effects			
	Radiation damage	x	x	x
	Isotope production	x		
	Transmutation doping	x		

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* Many of the elastic and inelastic scattering techniques can be time resolved and/or spatially resolved with increased resolution and usefulness as the brightnesses of future sources are increased.

(see references 5, 8, 17, 18, 19), would enhance the intensity of synchrotron radiation. These devices have been, and are being, added to the present generation of storage rings, although not yet to the maximum possible degree. Unfortunately, the appreciation of the role insertion devices could play came too late to influence in any major way the design and construction of our present generation of storage rings.

The fourth generation of synchrotron radiation facilities, now technologically possible, involves the construction of new storage rings designed to maximize the brightness of the radiation from insertion devices. Such rings offer brightness increases by factors of from 50 to more than 100 over the best synchrotron radiation sources we have today or that we can achieve by adding new insertion devices to existing facilities. No dedicated facility that can produce undulator quality radiation in the x-ray region exists at present. Using the orders of magnitude increase in brightness that will be achieved with a new 6 GeV facility, we will be able to conduct entirely new types of experiments, some of which will open up major new research areas.

Synchrotron radiation has already contributed to many aspects of materials science as well as to other fields. Some of the more important contributions are outlined below. More extensive descriptions may be found in references 5, 8, 18, and 20, and in the references therein.

The simplest experiment, and one of great importance, centers about the measurement of photoabsorption by atoms, molecules, and solids. The continuum of synchrotron radiation allows easy access to the core levels of many atoms and has revealed a variety of many-body phenomena, including giant collective resonances, so-called Fano (interference) line shapes, "missing" spectral lines, and the "spike" shape of some absorption edges in metals. These have contributed to a better understanding of many-body effects in both atoms and solids.

At energies above the absorption edges in solids, the extended x-ray absorption fine structure (EXAFS), which is produced by interference effects in the scattering of the ejected core electron, gives precise information concerning the local geometry of the absorbing atom. When increased brightness is available, the EXAFS technique can be extended to detect elements in bulk samples and submonolayer adsorbates on surfaces that are present in concentrations of parts per million. EXAFS gives site-specific, geometrical information regarding atoms in samples of many types, such as alloys, catalysts, and biological molecules. In most cases, the structural information obtained with the EXAFS technique was unattainable previously. Examples include geometrical information concerning the active site of the important nitrogen-fixing enzyme, nitrogenase; information relative to the active sites of important catalysts; structural parameters of impurities in coal and oil that make processing difficult; and studies of the role of impurities in determining important mechanical properties of materials.

Photoemission spectroscopy is widely employed at synchrotron radiation facilities. It provides independent information on initial and final electron states. Moreover, the anisotropy exhibited by atomic and molecular photoemission spectra gives information concerning atomic wave functions that is different from that obtained from absorption spectra.

Photoemission from molecules exhibits shape-dependent resonances that are studied in the gas phase and then used to determine the orientation of molecules on surfaces. The continuum of synchrotron radiation makes possible various forms of so called "yield spectroscopy," in which the absorption of photons is signalled by secondary events. In this way, one can, for example, selectively examine absorption in the region of a surface by monitoring the yield of Auger electrons. Similarly, one can determine the onset of bulk absorption by monitoring the emission of characteristic x-rays. Brighter synchrotron radiation sources have permitted angle-resolved photoemission experiments that give electronic band structure, including symmetry, directly from the data. These experiments yield fundamental energy band information for solids, surfaces, and adsorbates, and thereby provide the basis for a more complete understanding the electronic properties of matter.

While EXAFS and photoemission spectroscopies have been pursued since the advent of x-ray and VUV synchrotron radiation based research, x-ray scattering and direct imaging technologies are just beginning to be carried out with the newest generation of insertion devices and storage rings. In spite of the limited time in which they have been available for exploration, these facilities have already shown that they can be used to obtain significant results. This gives us confidence that research based on synchrotron radiation will benefit dramatically from the next generation of facilities employing insertion devices. The scattering of x-rays by monolayer adsorbates and freely suspended thin films that are two monolayers thick has already been successfully demonstrated. In addition to opening the techniques of x-ray crystallography to the world of surfaces, thin films, and interfaces, synchrotron radiation has permitted exploration of the scientifically important phenomena associated with two-dimensional phase transitions.

The increase in intensity offered by the newest storage rings has enabled the study of bulk crystals that are as small as 1 m in size, thus permitting the determination of the structure of many important materials, such as synthetic zeolites, that can only be grown in the form of very small crystals at present. The use of anomalous x-ray scattering promises to help solve the difficult problem of determining scattering phases that has plagued crystallographic studies of important large macromolecular systems. The pulsed nature of synchrotron radiation has been used successfully to study the technologically important process of laser annealing of silicon as well as the scientifically important problem of muscle action in animals. The initial experiments in which synchrotron radiation is used for angiography have shown real promise of improving this medically important diagnostic procedure dramatically (reference 8).

Summing up, the first three generations of synchrotron radiation have already provided us with a revolution in the capabilities for using photoemission and EXAFS techniques and have demonstrated great promise for employing scattering and imaging to advance many areas of science and technology. Insertion devices, particularly undulators, will advance the areas approachable with the use of photoemission and EXAFS techniques further and provide dramatic new opportunities for scattering and imaging.

The topics described above indicate what can be done with the newest sources of synchrotron radiation. More important are the even more complex research problems that can be undertaken with new storage rings that are designed specifically to use insertion devices. Examples are given below.

Condensed-Matter Physics

A major fraction of research using synchrotron radiation, both x-ray and soft x-ray, has involved the field of condensed-matter physics. There is a large number of new applications that cannot be addressed because of limitations of sources or instrumentation, or both.

Photoemission Spectroscopy. Photoemission spectroscopy is the primary technique for studying the electronic structure of solids, surfaces, adsorbates, and interfaces. On the basis of experiments being carried out at the new synchrotron radiation facilities, we can foresee what can be done with yet brighter sources. Angle-resolved photoemission provides understanding of the electronic band structure, including the band structure of the surface. The sample may be a crystal or an ordered overlayer. The resolution of angular and energy distributions has been increased with sources of higher brightness and have revealed new structures. Additional resolution is mandatory for the study of any material with a large unit cell, either in the interior or on reconstructed surfaces. Recently, measurements of spin-polarized photoemission have been carried out with synchrotron radiation. When combined with angle resolution, this procedure allows determination of the band structure of magnetic materials, including the spin labels for the bands. This is a technically difficult experiment. In particular, polarization detectors are notoriously inefficient. Brighter sources are mandatory if this technique is to be used widely.

At higher photon energies, one enters the region of x-ray photoemission in which the binding energies of core levels and the density of states for the valence electrons may be probed. Commercial equipment for this type of measurement with a resolution of approximately 0.5 eV at fixed photon energies is available. A synchrotron radiation source of the next generation would offer both higher resolution and higher sensitivity than anything possible today, thereby improving the utility of this already useful spectroscopy. Of perhaps greater significance is the extension of photoemission spectroscopy to procedures providing time and space resolution. This would make it possible to study surface reactions and to carry out microprobe studies of photoemission.

Surface Science. Other techniques for the study of surfaces also are benefitting from higher brightness sources. One is surface EXAFS, in which an absorbed x-ray excites a surface atom or molecule and a fluorescent x-ray or an Auger electron is then detected. The spectra give precise geometrical information on the location of the surface species. Photoelectron diffraction gives similar information. Both these techniques provide gains in surface sensitivity as the source brightness increases, and allow the study of surface species at ever great dilution. Finally, the new areas of photon-stimulated desorption of species from the surface requires sources of higher brightness. Both neutral and charged atoms and molecules, in their ground and excited states, can desorb from surfaces during photoabsorption. This may be the most site-specific surface phenomenon known. The photon flux used must be high because of the possibly small number of desorption sites and the low probability of release.

X-ray Scattering. X-ray sources of higher brightness are ushering in a new era in x-ray scattering. One can now work with surfaces, thin overlayers, and even freely suspended membranes. The crystallography of reconstructed surfaces can be determined, as can that of monolayer adsorbates. Thus, the crystallographic technique responsible for determining most of the known bulk structures can be extended to surfaces and thin films with insertion devices. This can be done as a function of temperature, to follow the structure and dynamics of quasi-two-dimensional melting. In fact, the study of phase transitions in two dimensions is providing important tests of theories of the behavior of the two-dimensional world of surfaces and thin films. Magnetic x-ray diffraction has been observed recently on the 54 pole wiggler at Stanford and promises to be comparatively routine when the brightest available x-ray wiggler sources can be used. Magnetic diffraction can provide much information concerning the magnetic structures of solids when an x-ray undulator on a 6 GeV source is available, and thus will complement traditional neutron studies, especially for materials for which only small samples are available. In some cases, surface magnetism may also be studied.

Inelastic X-ray Scattering. One field almost completely neglected in the first three phases of the evolution of synchrotron radiation has been inelastic x-ray scattering as related to the dynamic properties of the system being studied. The brightness of the radiation is most important for such research. Inelastic scattering of x-rays can, in principle, be used to probe both the electronic properties, such as those of plasmons, as well as collective atomic properties, such as lattice vibrations. However, achieving the 10^{-2} to 10^{-3} eV energy resolution needed will require the brightness provided by insertion devices and by major new instrumentation.

Atomic and Molecular Physics and Chemistry

Gas-phase photoemission has contributed extensively to our knowledge of atoms and molecules. Early studies emphasized the "static" study of excited states, the decay channels being inferred from line shapes. As the brightness of sources increased, the decay products, such as ions, electrons, and photons, could be detected. Finally, coincidence experiments began to be carried out, leading to more precise information regarding the nature of the excited states. Gas-phase experiments always require high brightness sources, for the sample is necessarily dilute.

The next-generation sources will permit several new classes of experiments. We already can work with gases at high enough resolution to excite single vibronic levels in molecules. These excited states can then be probed by high-resolution laser-spectroscopic techniques. Moreover, when source brightness becomes adequate, a molecule in an excited state can be made to interact with another molecule, bringing in an era of state-to-state photochemistry. These experiments are not possible with present sources because none have adequate brightness. Moreover, the time structure is not favorable.

The next-generation source will have pulse lengths shorter by a factor of about five relative to those now available. Such time structure will permit fluorescence spectroscopy from excited states on a time scale of a few picoseconds--shorter than the radiation pulse itself. This capability will, for example, make it possible to determine structural and dynamic properties of large molecules in solution and to study atomic and molecular reactions on surfaces. It will also be possible to use molecular beam techniques.

Biology and Medicine

EXAFS and x-ray crystallography involving synchrotron radiation have been applied to biological systems in the past. EXAFS has been useful for obtaining detailed information on large biomolecules such as hemoglobin. It is especially useful for molecules with a functionally important minority constituent, such as a metal atom in an enzyme. With increasing source brightness, it is possible to work with larger molecules having fewer active elements per unit volume. Time-dependent studies in which the structural response of the active site in the molecule to a chemical perturbation is determined become possible. Time-dependent x-ray absorption spectroscopy has already been used to follow the Fe absorption edge as the iron in myoglobin recombines with CO after laser-induced flash photolysis of carboxymyoglobin (references 25, 26). This was done on a 300 sec time scale with an existing storage ring. Better time resolution is possible, but EXAFS measurements on such a time scale await a source with higher brightness.

In studying x-ray damage to biological molecules and crystals, it has been found recently that the reciprocity law breaks down, and less damage results if the radiation dose is delivered at high rates for a short time. Therefore, higher-brightness sources offer the opportunity to work with smaller crystals, including those of molecules difficult to crystallize. They also make it possible to collect more data before samples become so badly damaged as to impair resolution.

Element-specific imaging represents the principal foreseeable application of synchrotron radiation to medicine. One form of coronary angiography used today involves the imaging of the coronary arteries in real time by K-edge absorption of iodine which is added to the blood. The classical technique is invasive, and provides relatively low resolution. In-vivo angiographic studies of animal hearts with synchrotron radiation are noninvasive, fast, and provide higher resolution. Studies on human hearts are planned and, if they are successful, should provide novel approaches to studies of atherosclerosis and, eventually, to clinical applications. A high-field wiggler would represent the only foreseeable source for such work with present machines, but bending-magnet radiation from a 6 GeV ring could facilitate applications of this technique.

Earth Sciences

The earth sciences provide opportunities for the application of synchrotron radiation in connection with microprobe analysis. Such analysis is now carried out with electron microprobes. Synchrotron radiation can also be used in x-ray diffraction studies at high pressures. A principal need is for structural characterization of minute crystals and zoned, or multi-domained, larger crystals. Higher brightness than is now available will benefit such research.

Imaging and X-ray Microscopy

There are several methods for achieving element-specific imaging, all at a relatively primitive stage of development. These include microprobe analysis, microscopy with zone-plates, and contact "lithography." As source brightness grows and the coherence of the radiation from soft x-ray undulators increases, microscopic holography and soft x-ray diffraction will become feasible. Both processes promise to give three-dimensional images of microscopic biological elements with a spatial resolution down to about 50 Angstroms. Available new sources will allow demonstrations of these techniques, which can be applied to study phenomena within a single cell. An undulator on a next-generation storage ring will make it possible to carry out useful and wide-ranging studies on such systems, employing radiation that "sees" only one element at a time.

Electron microscopy cannot be applied readily to living cells. However, holographic imaging techniques may make it possible to work with living cells, or at least with cells that have been processed less than is now the norm in electron microscopy. The imaging can be carried out on a millisecond time scale and with submicron resolution. The source needed for such imaging, an undulator on a 1 to 2 GeV next-generation storage ring, will have coherence properties similar to those believed achievable with VUV and soft x-ray harmonics of visible and UV lasers. In fact, at shorter wavelengths, the undulator should provide higher average power than laser based sources (reference 27).

The foregoing selective examples show that synchrotron radiation is used for many purposes by scientists from a variety of disciplines. Research groups are combining the use of synchrotron radiation with other techniques, such as molecular beam epitaxy, pulsed lasers, and electron energy loss spectroscopy.

The versatility and power of research based on the characteristics of synchrotron radiation have emerged in the past 15 years. With the new capability provided by insertion devices, primarily undulators, the future impact of these devices will be even more profound.

NEUTRON SCATTERING RESEARCH: PAST AND FUTURE

Worldwide neutron scattering facilities and research applications have grown dramatically during the past decade. The most notable example is the emergence of the British/French/German center at the Institut Laue Langevin at Grenoble. But the Grenoble facility is only part of a major transformation of the field throughout Western Europe and more recently in the United States and Japan.

A New Generation Of Instruments: Europe And The United States

Over the past 25 years, the unique characteristics of the neutron as a probe of condensed matter has transformed much of our fundamental understanding of the physics and chemistry of materials. In keeping with this, a new generation of cold and thermal neutron instruments has been developed during the last decade, particularly in Europe. These have extended the wavevector range and energy resolution for neutron experiments by orders of magnitude. And they have, in turn, made possible new research in physics and chemistry and greatly expanded the applications of neutron scattering to new areas--materials science, polymers, and biology. Thus, the neutron scattering community in Europe has tripled in the past decade, and, more recently, the neutron scattering community in the United States has nearly doubled. This growth has also been stimulated by the emergence of higher-intensity pulsed neutron sources which by providing higher neutron energies have created new opportunities for neutron scattering research (reference 7).

The emphasis at current steady state reactor centers in the United States has been primarily on forefront research rather than on the development of instrumentation. This has been dictated, in part, by the U.S. neutron funding profile. By necessity, and in contrast, the pulsed source programs at Argonne and Los Alamos have emphasized development of pulsed source instrumentation and techniques, although important research has also been accomplished there.

Early neutron scattering research focused primarily on the exploration of basic issues in condensed-matter science. These issues included phonon and magnon dispersion relations, the structure of hydrogenous materials, crystallographic and magnetic structures in simple solids, and phase transitions in model systems. In the past decade, the range of systems under examination has broadened considerably, and the scientific issues have often become much subtler. Neutron scattering has thus become an essential tool, providing unique structural and dynamical information central to the elucidation of the physics, chemistry, and other attributes of systems that are typically of interest to very broad communities. This change in character is evident in the outstanding accomplishments involving the use of neutrons in the last decade at major centers around the world.

These accomplishments include elucidation of (a) the structures and transitions in magnetic superconductors, (b) the physics of disordered magnets including metallic glasses, percolating alloys, spin glasses, and random field magnets, (c) the structures and excitations of incommensurate systems, especially those involving one-dimensional mass and charge density waves, (d) tunneling modes in chemical systems, including deuterated solid methane and hydrogen trapped by impurities in metals, (e) stoichiometric rearrangement and diffusion mechanisms in fast ion conductors, (f) early stage nucleation of voids in metals, (g) single polymer chain configurations in bulk polymers as well as composite polymer materials, (h) the spatial organization of macromolecular assemblies such as ribosomes, and (i) the location and exchange of hydrogen in proteins.

Finally, there have been important contributions to basic particle physics, including the determination of an upper limit on the electric dipole moment of the neutron, an upper limit on the occurrence of nonlinear terms in the Schrödinger equation and limitations on the incorporation of gravity in the Schrödinger equation. In all of these cases, neutrons have played an essential role.

In spite of major contributions to these and other impressive accomplishments, the current state of the U.S. neutron facilities is unsatisfactory. The broadening of the scientific base of neutron scattering necessitates the development of new capabilities at existing facilities with a new generation of instrumentation. Further, by the mid-1990's our existing reactor sources will be 25 to 30 years old, so that their long-term viability becomes a serious issue. In addition, many experiments of current interest turn out to be signal- or resolution-limited, so that greatly increased fluxes are required. This can be achieved by developing a new steady state reactor and a new pulsed spallation source.

Against the above summary of past accomplishments, the Committee describes areas of materials research and other fields in which neutrons can be expected to make important future contributions if advanced instrumentation and new facilities are developed in the United States.

Condensed-Matter Physics

A major fraction of neutron scattering research traditionally has been directed toward condensed-matter physics. Concomitantly, there is a continuous stream of interesting and important physics problems for which neutrons provide essential information. There are, however, a quite large number of problems in condensed-matter physics of immediate importance that cannot currently be addressed in the United States because of limitations on instrumentation or flux. This class of problems is discussed below with emphasis on four research areas.

First, as a result of rapid progress in the techniques of materials fabrication, a remarkable variety of lamellar materials can be synthesized. In all of these, there are important structural and lattice dynamical questions that often can be addressed only with the use of neutron scattering. Examples include artificial multilayer materials such as GaAs/$GaAl_xAs_{1-x}$, and CuNi. High-resolution studies of superlattice effects in the phonon dispersion relations are surely needed. Other important low-dimensional systems include graphite intercalation compounds of which very high quality but rather small (about 0.5 mm^3) single crystals have recently been produced, and also hexatic smectic liquid crystals. Studies of in-plane dynamics of the intercalates and of excitations in hexatic phases would yield fundamentally new results. A related and rapidly-growing area of research centers about the determination of the structure and dynamics of adsorbed species of molecules, especially hydrocarbons on high surface area substrates. All such studies would require high resolution and a copious flux of cold neutrons.

Second, in studying highly disordered magnets involving competing interactions, such as spin glasses and random field magnets, it has been found that important new effects occur in the time domain; for example, the system gradually freezes into a metastable state with decreasing temperature. Moreover, pronounced hysteresis effects that depend on the prior history of the sample are observed. This class of problems, which promises to grow in importance over the next decade, requires use of the very high energy resolution provided by the spin-echo technique.

A third new area of materials research relates to the study of nonequilibrium phenomena such as spinodal decomposition in supersatured alloys and turbulent flow in anisotropic liquids. The advent of wide angle position-sensitive detectors and modern data acquisition systems provides important new opportunities for such studies. Using a next-generation reactor source, one may expect to collect complete powder diffraction or small-angle scattering patterns with reasonable statistical accuracy for periods of time between 0.01 and 0.1 sec. This will allow probing the early time behavior of such systems.

A fourth area of research that has always been severely limited by both flux and instrumentation is the scattering of polarized neutrons. Polarized neutron techniques allow separating magnetic and nuclear scattering as well as coherent scattering and incoherent scattering arising from nuclear spins. An order of magnitude increase in flux, with improved polarizers for neutrons of short wavelength, would make many new experiments possible. Examples include studies of the excitations in magnets above the thermal transition temperature, elucidation of the spin dynamics in rare earth materials with mixed valences, separation of the magnetic scattering in spin glasses, and studies of magnetic defects in antiferromagnets.

There are, of course, always many important materials where, in spite of the best efforts of crystal growers, small sample size limits or prevents the full range of useful neutron experiments. Examples include Nb_3Sn, Nb_3Sb, $MEM(TCNQ)_2$, $ErRh_4B_4$, as well as others mentioned above. An order of magnitude increase in flux would bring many such problems into reach.

Finally, the increased neutron flux in the epithermal range will enable access to important new information on high-energy magnetic excitations in transition metals, actinide compounds, rare earth metals, and intermetallic compounds. Experiments involving the determination of the single particle momentum distribution in He^4 and He^3 as well as other light atom systems can also be anticipated.

Materials Science

Polymer and Colloid Science. The availability of small-angle neutron scattering (SANS) facilities has led to revolutionary advances in polymer science over the past decade. As indicated earlier, the substitution of deuterium for hydrogen makes it possible to extract information concerning the global molecular geometry of polymer molecules in the presence of high concentrations of other polymer molecules having the same chemical structure but differing isotopic compositions. There are at present no other experimental methods for making such measurements. Results have stimulated significant advances in understanding that, in turn, have led to new experiments. These SANS experiments have been carried out primarily on an instrumented cold neutron guide at Grenoble, although useful work has been achieved at new U.S. facilities. Important accomplishments include measurements of the conformation of single molecules in dilute and concentrated solutions and in amorphous bulk polymers. The state of miscibility of polymer blends and the state of aggregation of polymeric superstructures can also be characterized.

Extensive exploration of molecular interactions and phase diagrams over a range of temperature, concentration, and pressure will be required in the future. Those experiments will be dependent on greatly increased fluxes to achieve realistic data collection times. There is also a compelling need for studies of the dynamics of polymeric systems in real time--including phase transformation rates, deformation rates, annealing, and conformational changes. Measurements at lower wave vectors (q) are also needed to enable one to look at progressively larger polymeric molecules. Such new applications require modern SANS instruments located on cold source guide tubes with copious fluxes.

So far, only a limited number of low-energy inelastic scattering experiments have been reported in polymers. Here one is especially interested in low frequency motion in which long sections of the polymer molecule move in concert. Real advances require the development of spin-echo spectrometers, which also incorporate high-q resolution, along with back-reflection spectrometry having high-energy resolution. Quasi-elastic neutron scattering instruments covering an extended q range, from 0.01 to 2 Angstroms^{-1}, could, for example, provide an integrated understanding of the high-frequency motions that determine the chemical and electrical properties of polymers, and the low-frequency motions that dominate their mechanical and transport properties.

Metals, Alloys, Ceramics. The start-up of the high-flux, SANS instrument at Grenoble in the 1970's, along with earlier ground-breaking work at Jülich and Saclay, marked a turning point in the use of neutrons for studying structural and related problems in metals and alloys. These instruments made it possible to examine heterogeneities in bulk samples at small wave-vectors without multiple scattering. Important failure mechanisms in these materials are associated with the formation of small voids, often located at grain boundaries. These include radiation damage, hydrogen charging effects, high temperature fatigue, and creep. In the past, the small size of these pores and their low fractional volume made it difficult, if not impossible to obtain statistical information or to follow the growth and linkage leading to failure. Such studies are vital to test competing theories in these areas.

Another important use of SANS has occurred in the study of clustering and precipitation phenomena in alloys as well as in the investigation of internal oxidation. Here, again, important tests of theory, such as scaling laws, are occurring. Activities by U.S. scientists in this growing field which uses SANS facilities recently developed in this country, as well as the Grenoble instrument in Europe when available, to obtain additional sensitivity or resolution, are already making major contributions.

In spite of the progress that has already been made, the application of SANS to the study of microstructure and distributed damage in real engineering materials is at an early stage. There is a need to investigate the formation of voids and precipitates in steel and other structural alloys from a very early stage of development, emphasizing size and volume fraction. The exploitation of this and other major opportunities in the next decade will require the development in the United States of much higher intensities of neutrons of long wavelength, along with more efficient and effective collimation and area detection systems.

The attainment of much higher intensity SANS instruments will also permit the kinetics of processes such as precipitation, phase decomposition, and grain coarsening to be followed in real time, on a scale of about 0.1 sec or greater, under realistic conditions of temperature and stress. Higher sensitivity and resolution, as well as longer neutron wavelengths, will be needed to test models of damage accumulation that lead to failure of materials and of structures. Such capabilities will also be important for new areas, making possible, for example, in-situ studies of densification of ceramics at various stages of processing.

Other recent advances include the rapid development of high-resolution powder diffraction equipment at pulsed neutron and reactor sources. This not only permits the determination of the structure of materials such as complex ceramics and catalysts, which cannot be obtained in single crystal form, but also makes possible the study of residual and interaction stresses as a function of depth in metals and multiphase materials. Energy-dispersive pulsed source techniques have proven to be particularly useful in many of these studies. It is clear that such investigations will increase in importance in the next decade, particularly as much higher neutron intensities become available, allowing the stresses in smaller-volume elements in structural materials, and more complex structures, to be probed.

Chemistry

The most exciting opportunities for applying neutron scattering to condensed-matter chemistry in the next decade will require the development of instrumentation with very high resolution and high sensitivity for both elastic and inelastic scattering. In dynamic studies, this is particularly true for low energy cold neutron spectroscopy (0 to 20 meV) and quasi-elastic scattering, in which the use of neutrons provides unique information relative to other approaches. There is a growing interest in fundamental studies of rotational processes and interactions, tunneling phenomena, and ionic and molecular diffusion mechanisms in solids, as well as of molecular species bound in homogeneous and heterogeneous chemical media. The study of the dynamics of such systems on an atomic and molecular scale is of great importance, for example, in gaining understanding of the behavior and activity of catalysts and chemical absorbents, as well as of intercalated and layered materials. The studies will require energy resolutions between 0.1 μV and 0.1 meV, depending on the dynamic modes or processes being investigated.

Future applications of high-energy neutrons to determine vibrational spectra using pulsed or reactor sources will require considerably higher resolution as well as spectral measurements for variable wave-vector transfers. Experiments carried out under these conditions require much higher neutron fluxes to allow accurate measurements of line shapes and spectral intensities. This will, in turn, be necessary to test dynamic models of molecules bound in chemical systems. Moreover, many of the future applications of neutron scattering in chemistry will involve the measurement of high-resolution difference spectra, in which the signal from the species of interest is small in comparison with that from the surrounding medium. This small signal, coupled with the often small sample sizes, will accentuate the need for higher neutron intensities and new instruments. Measurement of difference spectra will make it possible, for example, to study the bonding, diffusion, and interaction of molecular species adsorbed in supported catalysts, as a function of the size of the catalyzing metal particles. Systematic studies using different catalysts, supporting substrates, and impurities are also of great interest.

In chemical crystallography, one of the requirements for neutron research in the next decade will be the extension of powder diffraction studies to ever higher resolution, so that more complex structures can be determined under wide ranges of temperature and pressure, for example, in ionic conductors, ceramics, catalysts, and even organic solids. High-resolution instruments will also be required to evaluate the details of disorder in complex stoichiometric and nonstoichiometric materials. For example, such new instruments will aid in the determination of the effect of incommensurate arrangements of oxygen and metal atoms in ceramics on the chemistry of these materials, such as titanates and niobates. In addition, studies of small single crystals, less than about 1 mm^3, of many new materials, including ceramics and inorganic complexes, will be required. Finally, there is a growing interest in real time, in-situ studies of atomic rearrangements occurring during solid state chemical reactions. All of these emerging applications require higher-intensity beams and greatly extended use of high-efficiency detectors and multidetector analyzers.

In the area of molecular liquids, the investigation of the relationships in dynamical behaviors of complex solutions, colloids, and micellar systems by small-angle neutron scattering and inelastic scattering will require high-resolution instruments currently unavailable in the United States, including considerably more intense sources of cold neutrons. This research is essential for understanding how the properties of such systems are affected by the concentration, complexing agents, and constituents of the surrounding medium.

Biology and Medicine

Studies of the structure and dynamics of biological molecules and molecular assemblies will continue to be of major interest during the next decade. The use of neutrons and photons has provided much of the major understanding that we presently have of the molecular structure of biological substances, and continued development of these uniquely useful probes is essential.

The principal growth in the use of neutrons will be in the wavelength range from 3 to 20 Angstroms. Shorter wavelengths are appropriate for the study of macromolecular crystals at the atomic level. Good facilities for such measurements presently exist at the Brookhaven National Laboratory and at the National Bureau of Standards, although additional facilities and higher intensities would be welcome.

There is a major need for further instrumentation and development in the area associated with cold neutron research. This domain will include structural studies of macromolecular assemblies at low resolution, possibly through the use of crystals but certainly with solutions. Selective deuteration methods will be extensively used. Such approaches have been used successfully in studies of the structure of lipoproteins, ribosomes, nucleosomes, and DNA-dependent RNA polymerase from *E. coli*. The analyses of many other macromolecular assemblies that may be amenable to neutron analysis now lie on the horizon, including studies of the RNA-protein complexes involved in processing messenger RNA and in controlling secretion. The higher-order structure of chromosomes is also of great interest and could be studied with neutrons of long wavelength.

Similarly, the study of biological membrane structure and the interactions of membrane components has provided a fertile area. Methodological refinements will permit a wider range of experimentation to probe both macromolecular interactions and membrane structures. Problems concerning the solvation of macromolecules, the formation of complexes between enzymes and substrates, and the interaction of ions with macromolecular surfaces are being pursued using scattering from solutions. Finally, recent applications of inelastic neutron scattering to macromolecules in solution suggest the possibility of obtaining fundamental thermodynamic parameters associated with macromolecular properties, and observing alterations in dynamic states that are correlated with functional changes in biological molecules. While this is a new area, success could lead to a greatly expanded use for inelastic scattering spectrometers that measure energy changes in the range from 0.01 to 100 meV. Thus, the needs for the coming decade in the neutron area are principally focused on the development and exploitation of instruments for cold sources.

Earth Sciences

Greatly improved energy-dispersive diffraction capability is required in the field of earth sciences. Here high-resolution diffraction of minerals at very high pressures, simulating geological stress conditions, is extremely important. Higher intensity pulsed sources will prove useful by permitting smaller samples and higher pressures to be employed. As in chemical crystallography, an order of magnitude increase in the flux from a steady state source would make it possible to greatly reduce required crystal sample volumes and open up a much larger number of mineral samples to investigation.

RESEARCH WITH MAGNET FACILITIES: PAST AND FUTURE

High magnetic field research is important for a fundamental understanding of a broad spectrum of material types and properties. Scientific advances in such diverse areas as superconductivity, permanent magnet research, and semiconductor science have all benefited from research based on the availability of intense magnetic fields. The attainment of such fields has, in general, been preceded by, and intimately connected with, applications developments and industrial commercialization. Each time a higher plateau of magnetic field strength is achieved, it is exploited quickly by the scientific community and is accompanied by the requirement for yet higher field strengths. The combination of high fields and low temperatures is particularly important, along with ancillary measuring equipment such as that associated with precision optical measurements.

The Francis Bitter National Magnet Laboratory is the primary high magnetic field research facility in the United States. Direct current (dc) fields in the 20 tesla (T) range are available using Bitter magnets. To reach higher fields, hybrid magnets utilizing both superconducting and resistive coils are required. Using such procedures, the National Magnet Laboratory has achieved a steady state field of 30.4T. The ultimate limit for dc hybrid magnets appears to be 35 to 45T, beyond which pulsed magnetic field systems are needed. The National Magnet Laboratory currently offers nondestructive pulse systems to 45T. Higher pulse fields, perhaps up to 100T, appear to be achievable using advanced technology. In addition, the National Magnet Laboratory provides limited high-field, low-temperature facilities as well as high field facilities coupled with a variety of ancillary measurement equipment.

A great deal of progress in a number of areas has been made using relatively low fields, of the order of 1 to 2T, but the number and types of useful experiments that can be performed increase dramatically with higher field strengths. For example, the Zeeman splitting of a single electron in a field of 1T is the energy equivalent of only 1.4K. Increasing the field to 100T raises the splitting to 140K, which is comparable to typical exchange and crystal field energies in many magnetic systems. This raises the possibility of inducing large changes in the electronic structures and behavior of both magnetic and nonmagnetic systems simply by applying of such large fields. Some recent examples of exciting high magnetic field experiments are studies of the fractional quantized Hall effect at semiconductor interfaces, measurements of important superconductivity parameters such as H_c in materials that have significant technological applications, and the newly observed magnetic field induced charge-density-wave transition in graphite.

Clearly, the ready availability of higher magnetic fields could enhance measurements currently being made and create new research opportunities. A study by the NRC Solid State Sciences Committee conducted in 1979 but still valid today concluded (reference 3) that the availability of higher magnetic fields would open up many new, exciting, and profitable areas of research. The study found that one of the areas profoundly affected is that of semiconductor research. As a recent example, clear data elucidating the quantized sub-integer Hall effect have been obtained in experiments up to 28T and at ultra-low temperatures (50-100 milli K). Although not totally understood, these results are thought to arise from collective effects which suggest the possibility of additional phenomena to be investigated at even higher magnetic fields and with improved ancillary conditions. Among such physical phenomena might be unusual effects associated with charge density waves and, in the low density limit, Wigner crystallization. The latter possibility is particularly interesting for a high mobility two-dimensional electron gas that can be achieved in a selectively doped semiconductor heterostructure. Such an experiment would require the 2d electron gas to be in the high field limit in order to reduce kinetic energy effects. Generally, such studies could have a major impact on improving our understanding of electron-electron correlation in an electron gas. Further, many of the techniques used to explore the electronic structure of semiconductors require that the cyclotron resonance frequency be high in comparison to the inverse scattering time of the electrons. For many materials, the scattering times are so short that this condition cannot be fulfilled with currently available magnetic fields. The only alternative in such cases is to go to higher magnetic fields. Other interesting phenomena in semiconductors that could be examined if sufficiently high magnetic fields were available include the breakdown in the effective mass approximation, electron-phonon "enhancement effects," and Zeeman splitting of deep impurity states.

Similarly, new scientific opportunities in metals and alloys emerge if intense magnetic fields are available. Many important metals and alloys have Fermi surfaces or parts of Fermi surfaces that cannot be measured at present, because either the effective mass or the electron scattering is too large. Both limitations could be surmounted in strong magnetic fields. Not only would it be possible to study the Fermi surfaces of exotic materials, but also of alloys well beyond the dilute limit. One might also envision measuring the Fermi surface of an alloy as it changed from the ordered into the disordered state. The age old problem of driving an exchange-enhanced paramagnetic system into the ferromagnetic state by applying a sufficiently large magnetic field might now be possible. Ferromagnetic Pd has not been found to date with the fields presently available. Increasing the upper limit for available magnetic fields might result in the induction of ferromagnetism in Pd.

The past several years have seen very exciting developments in the field of high-performance permanent magnet materials, especially new alloys based on the rare earth/iron/boron ternary compound, $Fe_{14}Re_2B$. The characteristics of these new materials for permanent magnets are based on large magnetization, very high magnetic anisotropy, and favorable microstructure. In a number of cases, such materials require magnetic fields in excess of 10T to achieve states near saturation. As improved materials become available, the field-intensity requirements may be even greater. The achievement of saturation fields is necessary not only in the production of permanent magnets, but in determining their fundamental properties from single crystal and oriented powder measurements. This provides a clear example of a field of research in which the availability of high magnetic fields could have a significant impact on major technological developments.

As discussed in the overview of this chapter, the study of superconductivity is the area of research that is most strongly linked to the production of high magnetic fields. Among materials currently being studied because of their interesting potential for use in high magnetic fields are the Chevrel phases, the B1 and A15 structures, as well as various types of thin film and inhomogeneous superconductors. High magnetic fields are also essential for probing those fundamental properties of superconductors that can be used to test microscopic theories, such as those associated with certain types of electron pairing--singlet, triplet, etc.—as well as other basic features of high field superconductivity.

In addition to research areas involving high magnetic fields in a very fundamental way, there is a vast array of fields involving spectroscopic and other techniques that use high magnetic fields as a probe for extracting important information about the properties of physical, chemical, and biological systems. For many of these, such as nuclear magnetic resonance (NMR), electron paramagnetic resonance (EPR), and the de Haas-van Alphen effect, the increased energy splitting available with higher magnetic fields provides tremendously enhanced ability to obtain information. At fields approaching 100T, energy splittings can also be great enough to have a direct effect on such phenomena as metallurgical phase transitions and chemical reaction rates. The ready availability of magnetic fields in these higher ranges would undoubtedly lead to a wide variety of applications and processes which utilize them in new and novel ways.

ADVANCED TECHNOLOGY NEEDS: APPLICATIONS OF NEW FACILITIES

The technological breadth of materials research can be sampled by looking at both the list of available applications in Table II.2 and the list of materials of economic importance in Table II.1. Technologically important examples have been described earlier in this chapter and are also given in numerous reports (references 1, 2, 3, 5, 6, 7, 8) dealing with synchrotron radiation, neutron scattering, and magnetic fields. Given below are examples of the connections between subareas of materials research and other fields which use major facilities and are linked to technological applications of national interest.

Semiconductors underlie all components involved in information systems--communication, computers, electronics. Techniques available at synchrotron radiation and neutron facilities are used to study structural and dynamic properties of semiconductors, including their interfaces, surfaces, and defects. X-ray scattering studies probe the atomic structure of semiconductors, while photoelectron spectroscopy techniques probe their electronic structure. Impurities of electrical importance in the range down to about 0.1 ppm or less, could be studied nondestructively using an x-ray microprobe on a new 6 GeV storage ring. High sensitivity, three-dimensional depth profiling of impurities and dopants in semiconductors and insulating films, can be studied with neutrons at concentrations down to 1 ppb if high-intensity cold neutron beams become available. X-ray lithography offers significant promise for fabricating precise submicron semiconductor structures for future VLSI applications. Doping by neutron transmutation is an essential tool for the production of semiconductor elements.

Essentially all other electronic materials, including metals, insulators, polymers, ceramics, and magnetic materials, can be characterized in unique ways using synchrotron radiation and neutrons. New structural and electronic properties of bulk and thin film materials, as well as interfaces, defects, and surfaces can be studied in novel ways.

The use of special techniques is crucial if we are to obtain an understanding of the interfaces which lie at the heart of the devices used in modern electronics. In addition to providing knowledge concerning semiconductor interfaces, synchrotron-radiation-based surface science and neutron depth profiling are also useful in exploring interfaces at junctions of metals and insulators with semiconductors, both of which represent important physical features of modern electronic devices. In the future, more intense sources offer the ability to study the time dependence of surface and interface reactions, as well as opening up the possibility of developing microfocused beam techniques.

Extended x-ray absorption fine structure (EXAFS) has been widely used by industrial researchers to study materials. Examples involve the local atomic arrangements in alloys, specific impurity sites in coal, and active sites of catalysts. EXAFS spectra have been taken of a catalyst operating in a fuel cell. Future examples include the study of new materials produced by ion implantation, studies of the role of minority elements in alloys, and studies of composites.

Increased brightness from new sources will make it possible to use smaller concentrations and to follow changes on a more rapid time scale. Parallel studies with an x-ray microprobe will offer spatial resolution as well, so that grain boundaries can be studied. Scattering studies of complex materials like oil and structural materials are providing a microscopic understanding of such materials for the first time. As was the case in the electronics industry, such understanding will contribute significantly to future innovations in the energy industries.

The availability of facilities for SANS and high-resolution neutron spectroscopy has led to revolutionary advances in the understanding of polymers and many other materials in the past decade. The availability of more intense neutron sources will greatly expand the technological uses of SANS. For example, capabilities for high-sensitivity SANS will be needed to study in-situ microstructures that determine the strength and performance of lightweight, high-strength alloys and superalloys for airframe members and engine components in military aircraft.

SANS studies of voids and very small precipitates produced in pressure vessel steels under irradiation in power reactors will provide valuable information. High-intensity, long-wavelength SANS and large-angle diffraction studies of bulk ceramics during various stages of densification as well as in-situ characterization of microcracks, pores, etc., which affect their durability, will be possible. Such knowledge may, for example, be of potential use when ceramics are employed in automobile engines. Cold neutron SANS and high-intensity neutron spectroscopy techniques will be needed for in-situ studies of the porosity, molecular behavior and interactions in new catalysts and feedstocks that are employed in the production of chemicals and fuels. SANS instruments using cold neutrons will allow the probing of biological assemblies consisting of enzymes, nucleic acids, and lipids, which control a large number of biochemical processes. These processes will often be relevant to biotechnological applications.

The unique characterization of materials with the use of high-intensity SANS will be available to study the polymeric constituents of new high-strength polymer blends and composites. This will include real time studies of phase separations related to processing. Such materials will provide increasingly important substitutes for heavier materials in autos, aircraft, and spacecraft.

Medical technologies are being advanced directly through the development of new diagnostic techniques. Moreover, the new light sources provide understanding at the microscopic level of many complex biological materials. A diagnostic example mentioned earlier is synchrotron radiation-based angiography. The study of platinum-based anti-cancer drugs by the EXAFS technique has provided clues to differences between effective and noneffective versions of these drugs. The production of medical isotopes using neutron sources will continue to be important in medical research, diagnoses, and therapy.

Synchrotron radiation and neutron facilities are important for the research programs of the defense agencies, both the Department of Energy and the Department of Defense. Advanced materials are of central importance to the defense agencies, which have needs ranging from information systems to structural materials involved in innumerable applications.

In a different class of application, remote sensors are employed in weapons tests, with particular emphasis on the hard and soft x-ray regions for diagnosis. Absolute absorption cross section spectra must be known, and detectors must be calibrated for such work. Both types of information can be obtained with the use of synchrotron radiation. While the temporal response of most detectors used in such work is faster than that of most synchrotron radiation sources, a next-generation storage ring will offer an improvement of about a factor of five.

There are several examples which illustrate the diverse applications of neutrons in research programs for national defense. High-intensity, energy-dispersive neutron diffraction is needed to measure local interaction stresses and textural characteristics which affect the performance of heavy metal shell components. Neutron depth profiling is needed to determine the tritium decay product (He^3) near the surface of refractory metals. High-intensity irradiation studies of metals and electronic components with fast neutrons are also essential.

In summary, the existing and proposed national facilities for materials research offer unique types of opportunities for both science and technology. It is difficult to think of significant issues affecting economic, defense, or health matters that cannot benefit in some essential way from the new opportunities presented by such facilities. This is, of course, the reason why they have already attracted the unparalleled participatory involvement of governmental and industrial research organizations. The new facilities considered in this report provide major opportunities for the next decade and beyond.

III. CONCLUSIONS AND RECOMMENDATIONS

The major facilities for producing synchrotron radiation, neutrons, and magnetic fields that are the focus of this report offer new opportunities essential for maintaining the progress and competitiveness of U.S. science and technology. These facilities will serve a broad spectrum of scientific fields, including materials research, biology, chemistry, atomic and molecular physics, plasma physics, the earth sciences, and medical science. As unique facilities offering incomparable scientific and technical opportunities, they will enable scientists and engineers to pursue otherwise inaccessible areas of science and technology. They will affect the technologies of information and defense, as well as those of energy, transportation, and health.

Materials research is the principal field served by these facilities. However, within this multidisciplinary field, there are also important research areas that are best served by specialized instruments of moderate cost that can be placed under the control of a single investigator or small group of investigators. Such research will often continue to be addressed most effectively by the Materials Research Laboratories and other relatively small and specialized research teams sharing comparatively small facilities, of the type described in Chapter I. Indeed, most of the research goals that the major facilities are expected to address originated through the insights of "small science" and will often be pursued jointly with groups also involved in small science.

The major materials facilities now operating--including those for neutron scattering, those for the production of synchrotron radiation, and the National Magnet Laboratory--are essential parts of the research effort of the United States. In some cases, these existing facilities will be superseded by new ones with additional capabilities. It will, however, be several years, and in some cases more than a decade, before the major new facilities recommended in this report can contribute directly to the national research effort.

The Committee emphasizes that its recommendations for major facilities--both new facilities and new capabilities at existing ones--embody two important prerequisites:

- That they are accompanied by expanded support of smaller materials research programs, including related instrumentation. Research on this scale continues to provide much of the fundamental new science in the field and to train a large fraction of our scientific and technical manpower.

- That resources must be provided to operate existing user facilities productively. In addition, the approved enhancements of major synchrotron radiation facilities at the Brookhaven National Laboratory, Stanford University, and the University of Wisconsin should be completed expeditiously, since it will require from several years to more than over a decade before the new facilities recommended in this report can contribute to the research effort of the United States.

RECOMMENDED PRIORITIES

The Committee's recommended priorities for the development and construction of facilities during the next decade include two categories:

- Major new facilities, and

- New capabilities at existing facilities.

These two categories complement one another in function, time and required resources. New capabilities at existing facilities are essential for scientific and technological needs during the next decade. The period from five years to more than a decade needed to construct major new synchrotron radiation and neutron facilities require that we start now in planning and designing these facilities. As discussed in Chapter II, failure to proceed with such new facilities will have an adverse and enduring impact on many fields of science and technology, diminishing the nation's competitive standing in such fields. The Committee concludes that both new facilities and new capabilities at existing facilities are essential for the effective evolution of science and advanced technology in the United States in the next decade and beyond.

The Committee also recommends the convening of additional panels to address other important aspects of materials research.

Major New Facilities

The Committee's recommendations for the construction of major new facilities are listed below in order of priority. A brief description and rationale is given for each recommended facility.

1. A 6 GeV Synchrotron Radiation Facility. This facility would effectively exploit the new scientific and technological opportunities made possible by insertion devices. These devices, by producing synchrotron radiation having orders of magnitude greater brightness than is currently available, would make it possible to expand on the seminal research using synchrotron radiation of the past decade. The first generation of storage rings designed as synchrotron radiation sources is now becoming operational, i.e., the National Synchrotron Light Source, at Brookhaven, and the Synchrotron Radiation Center, at the University of Wisconsin. While they will provide important capabilities, concurrent advances in design make it possible to construct storage rings and insertion devices with orders of magnitude improvement in brightness. A 6 GeV synchrotron radiation facility exploiting such advances offers both identifiable and as yet unforeseen opportunities for research not possible at present facilities.

This 6 GeV ring would have many long, straight sections containing insertion devices--undulators and wigglers. The storage ring would be designed to provide an electron beam that optimizes the emittance or intensity, or both, of synchrotron radiation from the insertion devices. A storage ring of about 6 GeV is optimal for producing undulator radiation in the 10 keV region where most x-ray research is done. The radiation from such a source would be orders of magnitude brighter than from any existing dedicated source. Wigglers on such a ring can provide unmatched intensity over a wide spectral region. The time-dependent characteristics of the radiation--short pulse length and long inter-pulse times--would make it at least as useful as that from existing sources. Moreover, insertion devices for the production of soft x-ray and vacuum ultraviolet radiation in the range from 100 eV to 1 keV would yield a thousand-fold brighter radiation than any source now operating, although not as bright as those possible on a new 1 to 2 GeV ring (Priority 3).

Timely construction of a 6 GeV synchrotron radiation facility would give the United States continued leadership in this important and dynamic field. Site-independent design should begin immediately, and the choice of site and construction should commence as soon as possible. If construction begins, for example, in FY 87, operation is possible by FY 92.

2. An Advanced Steady State Neutron Source Facility. The goal is to achieve about ten times the flux of existing machines with a minimum requirement of five times the flux. There are two principal reasons for the priority.

First, and most important, a new high-flux source can be designed to optimize beam geometry and flux distribution, so as to yield increased intensities for all experiments. An increase of about ten times the flux of existing machines is an aggressive but technologically feasible goal. Neutron scattering is inherently a signal-limited technique. The new facility would greatly increase the range of neutron experiments in materials research and other fields, as well as the precision with which relevant energies and momenta could be measured.

Such a neutron source would ensure the United States a leading position in this field, especially in the cold neutron range, where flux increases of an order of magnitude can be achieved. Such increases offer new capabilities, for example, in high resolution spectroscopy and studies of small angle scattering.

Second, the current high-flux reactors in the United States were all commissioned in the 1960's, so that there are significant concerns about their long-term viability. Given that design and construction of a new facility will require about a decade, planning must begin now to furnish needed capability for the late 1990's and beyond.

The Committee suggests that the design and construction of a new facility include the following: (a) at least one large guide hall containing many large-area guide tubes for cold and thermal neutrons; (b) a reactor hall containing many thermal beams, along with several "hot source" beams for high-energy neutron research; (c) a variety of spectrometers, including many with new capabilities beyond present designs; and (d) improved national facilities for isotope production, irradiation of materials, neutron activation analysis, and research in nuclear physics.

Instead of upgrading an existing reactor, a new facility should be built, and site-independent design should begin immediately. Because of the complexity of safety requirements, the Committee does not expect construction to begin until about FY 89, with completion possibly by FY 96.

3. A 1 to 2 GeV Synchrotron Radiation Facility. The Committee has concluded that, while the 6 GeV storage ring can furnish important new capabilities for the lower-energy region, a single such facility may not provide adequately for the national opportunities of the next decade. Among the reasons for this are: (a) the optimum storage ring energy for producing fundamental undulator radiation with wavelengths in the range of 10 Angstroms and greater is about 1.5 GeV, a region offering special opportunities for research in chemical physics and electron spectroscopy; (b) in addition to an increase in brightness, the unwanted total power density associated with a 1 to 2 GeV ring is significantly lower at wavelengths longer than 20 Angstroms; and (c) the undulator radiation from a 1 to 2 GeV source will have a higher degree of coherence than that from undulators elsewhere, thereby opening opportunities to apply various imaging techniques, such as microscopy and holography. A 1 to 2 GeV facility would provide optimal flexibility for both VUV and soft x-ray users.

This facility, then, would be centered around insertion devices but optimized for high brightness in the soft x-ray and VUV synchrotron radiation regions. The growth of research using these spectral regions has paralleled that in the x-ray region. Moreover, major advancements in design have occurred, permitting large increases in brightness for such a source.

4. A High-Intensity Pulsed Neutron Source Facility. Pulsed neutron facilities offer the best capability for sources of high-energy neutrons and the most promising approach to future advances beyond those that appear possible with steady state sources. In the few years that pulsed sources have been available, they have led to innovative research using new time-of-flight techniques and have served a broad user community, even though limited to modest peak fluxes.

The new capabilities recommended at existing facilities, for example, the attainment of a 10^{16} neutrons/cm^2-sec peak flux at the Los Alamos National Laboratory facility--Priority 3 in new capabilities given below--are expected to advance research using pulsed neutrons even further. Action on the design and construction of a pulsed source with a peak flux in the range of 10^{17} neutrons/cm^2-sec should be based upon the results obtained from such new capabilities.

New Capabilities at Existing Facilities

The Committee's recommendations for adding new capabilities at existing facilities are listed below in priority order. Brief rationales and descriptions are given for each recommendation.

1. Centers For Cold Neutron Research. Guide halls and instrumentation for exploiting the only cold neutron sources in the U.S., located at the Brookhaven National Laboratory and the National Bureau of Standards facilities, should be developed in an orderly fashion.

These facilities are urgently needed to address the rapid expansion of neutron applications in materials science, chemistry, and biology; many central problems in those fields can only be solved using new instruments with cold neutron beams. These centers will provide a diverse, flexible array of cold neutron instruments, matching current capabilities in other industrialized nations. Further, by using advanced techniques for beam focusing and polarization, such facilities would exceed existing worldwide capabilities, in areas such as high resolution spectroscopy of catalysts and polymer systems and in studies of impurities and inhomogeneities in bulk materials.

Research using cold neutron facilities has received inadequate support in U.S. during the last decade, a period of major investments in cold neutron research in other countries. The Western European investment alone is at least ten times that of the United States. There are only two cold neutron reactor sources in the United States one at Brookhaven and one being developed at the National Bureau of Standards. Guide halls, which improve the versatility and flexibility of cold or thermal neutron instruments, do not exist in the United States while there are six fully instrumented cold neutron guide halls either completed or under development in Western Europe. Implementing this priority will enable U.S. scientists to be competitive in cold neutron research during the next decade and will provide new instrumentation concepts for developing future neutron scattering facilities.

2. Insertion Devices on Existing Facilities for Synchrotron Radiation. Insertion devices and instruments should be developed in an orderly fashion to exploit about six of the remaining straight sections

of existing storage rings. The special characteristics of undulators as radiation sources should be emphasized, since they enable new capabilities not available presently at existing facilities.

Existing storage rings fitted with insertion devices will be our premier sources of synchrotron radiation for the next 5 years or more, or until new facilities described in this report are completed. Further, they will provide valuable experience for designing and implementing our next generation of synchrotron radiation facilities.

There are, currently, only four operational insertion devices, all wigglers. Nine new insertion devices have been proposed and approved for funding, of which only three are undulators. This number of insertion devices is clearly inadequate to meet future national needs and requires the development and implementation of additional devices.

Thus, the construction of additional insertion devices, when it is approved, should follow the construction of new capabilities at synchrotron radiation facilities already included in the budgets for FY 85 and FY 86.

3. Experimental Hall and Instrumentation at the Los Alamos National Laboratory. An experimental hall and new instruments at the Weapons Neutron Research/Proton Storage Ring (WNR/PSR) pulsed neutron source at the Los Alamos National Laboratory (LANL) would make the United States competitive in pulsed neutron research and would help guide the development of future pulsed sources. The expected flux increase at this facility provides an important opportunity to explore, at modest cost, the great promise of pulsed neutron science in relation to spectroscopic and structural problems. Although this technology is young, the instruments developed at the Argonne and Los Alamos national laboratories demonstrate that innovative approaches can produce enhanced capabilities.

Pulsed sources are superior to steady state sources in generating neutrons of short wavelength. It also appears that instruments for pulsed sources can be developed that will be advantageous at long wavelengths in certain cases. Developing the new source at the WNR/PSR at Los Alamos should, for a relatively modest investment, provide an important new tool for research and also permit a detailed assessment of the best course for developing future pulsed sources. Overall, the Committee feels that the WNR/PSR facility should be exploited fully. In considering the specific opportunity at Los Alamos, important factors taken into account were the peak intensity that could be attained (greater than 10^{16} neutrons/cm^2-sec), the relative economy of the investment, and the speed with which the facility could become operational.

4. Upgrade of the National Magnet Laboratory. The National Magnet Laboratory (NML) is the only high magnetic field user facility in the United States. Many areas of materials research require combinations of high fields and/or low temperatures. Both the 45T pulsed field system and the 19T/50 mK system at the NML require enhanced instrumentation to permit full exploitation. The position of NML as the leader in magnetic field research depends on the timely development of a new hybrid system that will provide higher fields at lower cost for a rapidly growing community of users. Additional funds are needed to

complete the project. A pulsed magnetic field system capable of 75T could also be placed on line more quickly with adequate funding. Recent experience shows that even modest increases in magnetic field capability can open new approaches for addressing important problems in condensed-matter science and increase the demand for NML facilities significantly.

5. Enriched Pulsed Neutron Source Target. Enriched targets exploit higher levels of fission to amplify the production of neutrons and can more than double the available flux. Such increases in flux are important because neutron scattering is inherently a signal-limited technique. The development and installation of enriched targets for use at pulsed neutron facilities would be cost effective.

Priorities 1 and 2 for major new facilities, when they are implemented, would serve as a centerpiece of this nation's future capability for synchrotron radiation and neutron based research. Thus, design and siting studies for a 6 GeV synchrotron radiation facility and for an advanced steady state neutron facility should begin immediately.

Because of the long lead time associated with an advanced steady state neutron facility, the immediate implementation of at least one instrumented cold neutron guide hall is necessary to provide forefront capability.

ESTIMATED COSTS OF THE RECOMMENDATIONS

To summarize the overall scale of its recommendations, the Committee presents, in Table III.1, its estimates of the requirements for new funding in millions of FY 85 dollars. The estimates in Table III.1 include costs of construction and initial instrumentation for major new facilities and new capabilities at existing facilities. Estimates for major new facilities assume initial instrumentation for one-half of the available beam line capability.

There are also additional costs associated with the development, maintenance, and scientific use of these advanced facilities. The Committee estimates related personnel costs to be about $250 thousand per year for each neutron or synchrotron end station. The same is true for major new magnetic field stations. A somewhat smaller amount is required for other experimental purposes and/or instrument maintenance. More detailed information can be obtained from the presentations included in the supplemental volume to this report. In addition, there will obviously be some incremental travel, subsistence, and experimental costs for the hundreds of scientists and engineers who will use these new facilities, costs which may be covered only in part by reassignment of funds used for other scientific purposes.

Table III.1 REQUIREMENTS FOR NEW FUNDING*

MAJOR NEW FACILITIES (Millions of FY 85 Dollars)

In order of priority:

1.	6 GeV SR Facility	$ 160
2.	Steady State Neutron Source Facility	260
3.	1 to 2 GeV SR Facility	70
4.	High Intensity Pulsed Neutron Source Facility	330

NEW CAPABILITIES AT EXISTING FACILITIES (Millions of FY 85 Dollars)

In order of priority:

1.	Centers for Cold Neutron Research	$ 25-35 each
2.	Insertion Devices on Existing SR Facilities	20
3.	Experimental Hall and Instrumentation at LANL	15
4.	National Magnet Laboratory Upgrade	5
5.	Enriched Pulsed Neutron Target	2-5

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* The Committee's estimates for construction and initial instrumentation costs are largely based on information from facility presentations, program officers, and other knowledgeable colleagues.

Major New Facilities

1. The new 6 GeV synchrotron radiation facility has an estimated cost of $160 million, including $125 million for construction and $35 million for instrumentation. The instrumentation would equip fully about 10 insertion devices, and associated beam lines, with about 20 experimental end stations. The estimated operating cost is about $20 to $25 million per year.

2. The new steady state neutron source has an estimated facility cost of $260 million, including $220 million for construction and $40 million for about 20 instruments. The estimated operating cost is $12 million per year.

3. The 1 to 2 GeV synchrotron radiation facility is estimated to cost $70 million, including $50 million for construction and $20 million for the instrumentation of 6 instrumented beam lines with about 12 end stations. The estimated operating cost is $9 million per year.

4. The high-intensity pulsed neutron source facility is estimated to cost $330 million, including $310 million for construction and $20 million for instrumentation of about 15 instruments. The estimated operating cost is $25 million per year.

New Capabilities at Existing Facilities

1. The centers for cold neutron research would cost $25 to 35 million each, about half for guide hall construction and half for instrumentation. The instrumentation funding would provide up to 20 cold neutron instruments and associated equipment. There are no incremental operating costs for the reactor associated with these new capabilities.

2. Insertion devices on existing synchrotron radiation sources would cost about $20 million for 6 fully developed lines, including about 12 x-ray and VUV instruments. There are no incremental operating costs for the associated synchrotron sources.

3. The experimental hall and instrumentation at the Los Alamos National Laboratory would cost $15 million and provide a large area for the installation of more than 10 instruments, 3 of which would be funded as part of the LANL proposal. Additional pulsed source operating costs of $2.7 million per year are required.

4. The National Magnet Laboratory upgrade requires about $5 million.

5. An enriched pulsed neutron target would cost between $2 and 5 million. Operating costs for the source would increase between $0 and 0.7 million.

Current major facilities will likely be superseded by the new facilities in certain cases, and their operating cost budgets will be transferred. An example is given by the steady state neutron source, whose construction could result in the phasing out of one of our current sources. This, in turn, would have the effect of requiring only a slight increase in net operating costs for the new facility.

The Committee considered possible funding schedules for each of the foregoing recommendations. In general, the new capabilities at existing facilities can be implemented within about 3 years from initial funding, whereas the major new facilities are estimated to require construction times from about 5 years to as long as 10 years.

In response to its charter, the Committee has determined the order of priority of construction of new facilities that are important for the rapid and effective progress of materials research and related fields. We show in Figure III.1 an estimated funding profile for design and construction associated with an expeditious implementation of all the items in these priority lists except for the 10^{17} neutrons/cm^2-sec pulsed neutron source facility, whose starting date is uncertain. The Committee does not necessarily recommend that all priorities be funded at the respective times indicated. The diagram is intended to suggest the approximate earliest possible start dates and construction time intervals for the various priorities. We note that accurate estimates of both construction costs and time schedules can only be obtained from specific proposals from specific institutions. The funding profile for priority 2 shown in Figure III.1b extends from fiscal years 1987 to 1989. Under this schedule, priority 2 modifications would follow the completion of those new capabilities at existing synchrotron facilities that are already included in the budgets for fiscal years 1985 and 1986.

With the foregoing in mind, several important general conclusions can be deduced from Figure III.1. First, implementation of new capabilities at existing facilities is complementary in time to the implementation of major new facilities. Second, with modifications of schedule, a relatively flat funding profile of construction is possible over the next decade, with an average expenditure rate of roughly $50 million per year for about a decade if all priorities are implemented. Third, the total construction fund of $588 million appearing in Figure III.1 is roughly comparable, in FY 85 dollars, to the average total U.S. capital investment per decade over the past two decades to provide facilities for synchrotron radiation, neutron production, and high magnetic fields, namely, in the range of $300 million, $500 million, and $20 million, respectively.*

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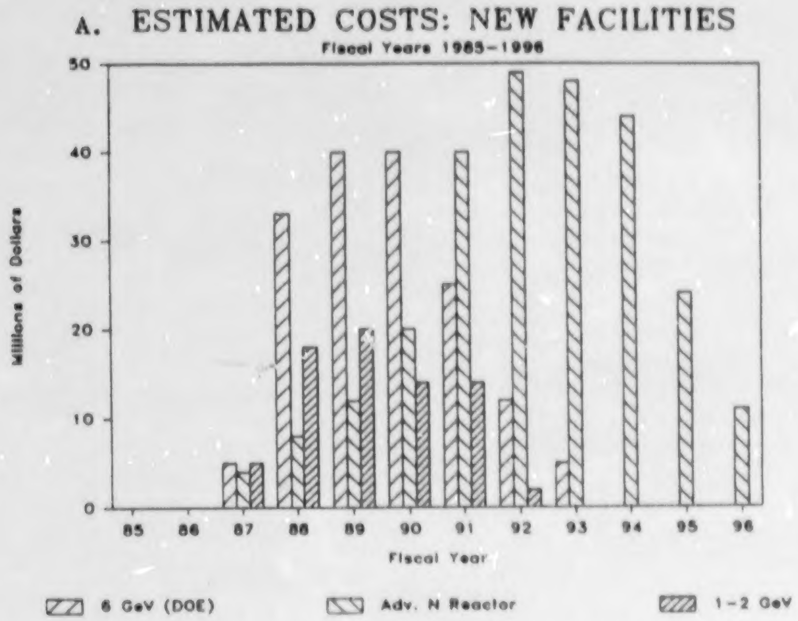
* The replacement costs in FY 85 dollars for existing multi-purpose neutron sources and related major instrumentation built over the past 20 years (primarily in the 1960's) is of the order of $500 million. This includes, for example, the HFIR at Oak Ridge, the HFBR at Brookhaven, the NBS reactor, the University of Missouri reactor, and the intense pulsed neutron source at Argonne. A comparable figure for synchrotron radiation sources and associated instrumentation (primarily developed over the past decade) is estimated at about $300 million including facilities at Brookhaven (NSLS), Stanford (SSRL), Wisconsin (Aladdin, Tantalus), Cornell (CHESS), and NBS (SURF II). Estimates for the synchrotron radiation facilities includes the construction cost of SPEAR at Stanford but does not include any share of other accelerator facilities used in a parasitic mode for synchrotron radiation at Cornell and Stanford.



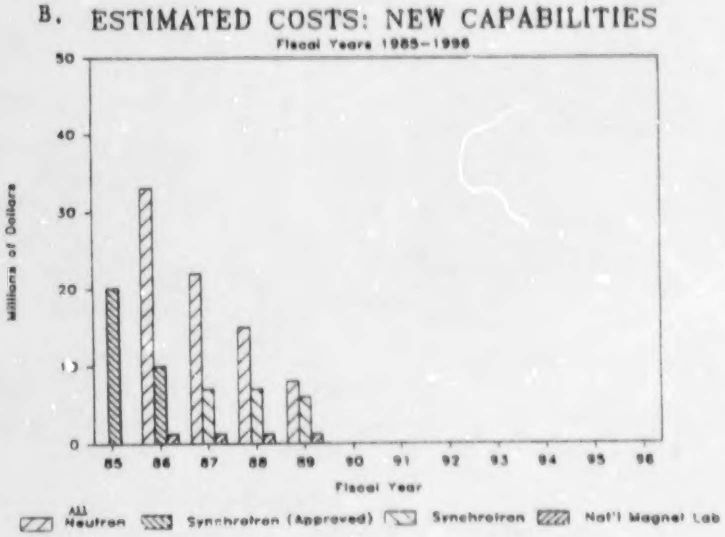


FIGURE III.1. Estimated Costs Versus Year. Estimated costs and earliest possible schedules for construction and initial instrumentation of (a) a 6 GeV synchrotron radiation facility, an advanced steady state neutron source, and a 1-2 GeV synchrotron radiation facility and (b) all recommended priorities for new capabilities at existing facilities.

The funding profile for priority 2 shown in Figure III.1b extends from fiscal years 1987 to 1989. In this schedule, modifications associated with priority 2 would follow the completion of those new capabilities at existing synchrotron facilities that are already included in the budgets for fiscal years 1985 and 1986. The Committee does not necessarily recommend that all priorities be funded at the respective times indicated.

OTHER SPECIALIZED FACILITIES CONSIDERED BY THE COMMITTEE

In addition to facilities for synchrotron radiation, neutron scattering, and high magnetic fields, the Committee surveyed other major facility needs and opportunities during the course of its study. However, none was identified that qualified for the priorities under the guidelines, namely $5 million minimum cost, established by the Committee's charter. We summarize here the specific items considered and the reasons for excluding them from detailed considerations.

Medium-Scale Specialized Facilities

The Committee briefly considered interdisciplinary materials research organizations, such as the Materials Research Laboratories (MRL) funded by the NSF and DOE, as well as special-purpose materials research laboratories or such centers for materials research as those on polymers, ceramics, and materials processing and other focused sub-areas of materials research. The Committee believes that such laboratories and centers represent a very important part of our overall national materials research program and that they fulfill national needs not otherwise satisfied by academic, governmental, or industrial laboratories.

The Committee heard excellent arguments for new facilities of this type, each of which can easily cost more than $5 to 10 million. However, the Committee excluded consideration of them without prejudice. It did so in part because of their "open-ended" nature. They require fuller definition through the formulation of specific proposals by specific institutions. The Committee did not request development of the details of such proposals when they were not already well formulated. Further considerations of important materials research laboratories and centers are deferred for future planning committees.

The Committee also discussed facilities for developing microelectronics processes. These are rapidly gaining national importance as microelectronic technology reaches submicron levels in silicon, and as materials other than silicon, such as gallium arsenide, are explored. Most large-scale facilities for microelectronics processing have, quite appropriately, been established by industry, though there is also a role for universities in this area.

Also discussed were facilities for high and ultra-low temperatures as well as those involving charged-particles such as electron microscopes and ion beam facilities, which can make major contributions to the analysis, synthesis, and modification of materials. The individual costs of these generally fall below the $5M threshold used by the Committee. As a result, and without passing any judgment on relative merits, such facilities would be better considered as part of the analysis of serious instrumentation needs mentioned earlier in this report. Such instrumentation will play important roles in conjunction with the use of synchrotron radiation sources, in which case their costs will be included along with those of beam lines.

Specialized Photon Sources

The Committee examined various other photon sources, such as high peak-power VUV excimer/dye-laser schemes, transition-radiation and bremstrahlung sources driven by intense relativistic electron beams, free-electron lasers, and soft x-ray sources derived from laser-heated plasmas. VUV laser sources based on nonlinear mixing of excimer and tuneable dye lasers were judged very promising. This technology deserves rapid development. The facility costs for such sources, although quite substantial when judged by traditional academic research standards, are expected to fall considerably below the Committee's $5 million threshold. Practical realization of the other photon sources listed above would require large capital investments.

However, only the free-electron laser appears to be of general interest at this time when employed in a user mode, because of its high brightness and broad tunability. This technology is currently under active development at many laboratories, both in the United States and abroad. The eventual utilization of free-electron lasers operating in the infrared seems a certainty. Efforts should be made to stimulate the establishment of a user community. The practical short-wavelength limit of such systems is not yet known, although operation of such lasers to 50 nm (5 nm with harmonic generation) has been projected. Considerable development effort is needed, particularly with regard to high-reflectance mirrors in this spectral region. Although it is premature to rank the value of free-electron lasers, they may eventually prove to be extremely important at photon energies in the range of 10 to 100 eV, and thus complement VUV/soft x-ray synchrotron radiation sources.

Computation Facilities

As indicated in Chapter I, the Committee also made an effort to examine the growing importance of large-scale computational support in the materials sciences. Theoretical materials science has now reached a point where, given adequate computer support, it can predict with quantitative accuracy, typically 1 to 10 percent, the physical properties of many materials systems, and thus complement experimental approaches.

The most effective kind of computer support for the national materials science community therefore is provided by a combination of a national network of Class 6 supercomputers and a number of smaller computers that are used by local or regional groups. The Committee strongly supports a major initiative in this direction now being undertaken by the National Science Foundation. It also strongly supports plans of the Department of Energy to extend the availability of networked supercomputers to scientists working in other areas. It hopes that other agencies supporting basic research will also take appropriate actions.

Muon Facilities

Pulsed muon beams, derived parasitically at high-energy particle accelerators, have received considerable attention for studies of condensed-matter physics that are based on measurements of spin-rotation. Several centers which support such research currently exist, and modest growth is anticipated. Some thought is being given to a major dedicated beam line at the Los Alamos LAMPF proton storage ring. The cost for such an addition may reach $30 million. It appears premature to judge the merit of such a facility, given the currently small size user community and the highly specialized nature of the technique.

Engineering Materials Test Facilities

Facilities in this category cover a very broad range with respect to the physical parameters studied and the associated capital costs. Major needs of this type for which federal, rather than industrial, funding is appropriate are primarily linked to mission oriented programs, such as national defense. As a result, they are not under the purview of the Committee.

Facilities Only Peripherally Related to Materials Science

Facilities whose principal purpose is not related directly to materials science were not considered by the Committee. An example is the proposal at Sandia for a Combustion Research Center (Phase II). The central thrust of this proposal is directed toward combustion science and technology. The behavior of materials at combustion temperatures is only one among a large number of other important topics projected for investigation at this laboratory as part of the new initiative.

National facilities for research in the physics of condensed matter

George H. Vineyard

Physics Department, Brookhaven National Laboratory, Upton, New York, 11973

L. M. Falicov

Department of Physics, University of California, Berkeley, California 94720

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Brief descriptions are given of 23 national facilities in the U. S. that are of importance to research in the physics of condensed matter. These facilities range from nuclear reactors and synchrotron sources to high-voltage electron microscopes and facilities for the preparation of special materials and submicron structures. They take a variety of forms and are located in several kinds of institutions, but are alike in being available to qualified scientists from other laboratories. The primary purpose, size, major experimental equipment, and method of operation are described for each facility.

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INTRODUCTION

At the American Physical Society meeting in Los Angeles in March of 1983 an invited poster session was held on National Facilities of Importance to Condensed Matter Physics. The session was arranged by the Division of Condensed Matter Physics. There were 23 facilities featured, ranging from nuclear reactors and synchrotron sources to high-voltage electron microscopes and facilities for the preparation of unique materials or submicron structures. Most of the facilities on display have come into operation within the last five years, many within the last one or two. This fact reflects the rapid increase in the importance of large research devices and combinations of large devices in condensed matter physics, together with the necessity that, because of their cost such facilities be developed on a national basis and widely shared. Thus a pattern of usage is developing in condensed matter physics which has been common in particle physics for many years, and institutional arrangements are evolving for accomplishing this objective effectively and fairly. All these central facilities are governmentally funded. Only two, however, are operated directly by the federal government; the others are operated by contractors, many in national laboratories, some in state universities.

Even though the 23 facilities included all of the very large national facilities which are of prime importance to condensed matter physics, the display was not exhaustive. Other facilities exist that were not included because of space limitations. The list, however, gives an excellent view of the present national posture. It shows that the United States is in a strong position, but also makes it clear that condensed matter physics is a dynamic area in which rapid growth and frequent change must occur. It is hoped that this review will be valuable to potential users and will assist in the wide dissemination of information on what is available and how the interested researcher goes about gaining access to these centers.

It is evident that a strong trend toward national user facilities is still in full swing, and that more centralized facilities for condensed matter research will soon become available. Decisions on what new centers are most needed should be aided by this overview of what exists now.

In the following, a short synopsis of each facility is given, including its primary purpose, major equipment, size, and method of operation. Sources from which one can obtain more information are also provided.

The facilities are grouped under the following headings: (1) neutron sources; (2) synchrotron radiation sources; (3) facilities for microanalysis, microfabrication, and surface studies; (4) electron microscopes; and (5).

The writers are indebted to the operators of the various facilities for their cooperation in supplying information.

I. NEUTRON SOURCES

Nuclear reactors have been the traditional sources of neutron beams for condensed matter physics since the 1940's. Four U. S. reactors which are national facilities are described in this section. Also included is a facility within a facility, the National Center for Small Angle Scattering Research at Oak Ridge.

More recently pulsed neutron sources driven by medium energy accelerators have come on the scene, and two of these which are now national facilities are represented.

The main focus in what follows is on neutron scattering; radiation damage in materials has not been emphasized. Most of these facilities, however, also offer capabilities for exposing specimens to various kinds of radiation.

A. High Flux Beam Reactor, Brookhaven National Laboratory, Upton, NY

The High Flux Beam Reactor (HFBR) provides the scientific community with one of the most intense thermal neutron sources in existence today. The HFBR began operating in 1965 at a power of 40 MW. It has had a cold neutron

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facility with liquid-hydrogen moderator operating since April 1981. The reactor was recently upgraded and has been operating at 60 MW since September 1982. Many types of experiments are possible at the HFBR, including magnetic and nonmagnetic structure studies, phonon and magnon dispersion measurements, and diffuse scattering studies. Because of the relatively high energy resolution and the sensitivity of neutrons to magnetic moments and to the nuclei of almost all elements of the periodic table, neutron scattering makes feasible many studies which would be difficult or impossible with x rays. Facilities of interest to solid-state physicists at the HFBR include several triple-axis neutron spectrometers which can be used for both elastic and inelastic scattering measurements with incident neutron energies between 2 and 200 meV. A wide variety of different sample environments is available, including temperatures from 35 mK to 1500 K, magnetic fields up to 7 T, and pressures up to 35 kbar.

For additional information contact B. H. Grier or G. Shirane, Physics Department, Brookhaven National Laboratory, Upton, NY 11973.

B. High flux isotope reactor, Oak Ridge National Laboratory, Oak Ridge, TN

The High Flux Isotope Reactor serves the condensed matter physics community by providing high-intensity beams of thermal neutrons. The scattering facilities available include eight different instruments, not counting the 30-m Small-Angle Neutron Scattering (SANS) instrument described elsewhere. They are: (1) the triple-axis polarized-beam spectrometer, which permits polarization analysis experiments; (2) and (3) two general-purpose triple-axis spectrometers used for most of the phonon dispersion measurements, but which are also useful for modest resolution quasielastic studies and fairly high resolution powder diffraction studies; (4) a liquid diffractometer with a linear position-sensitive detector; (5) a double perfect-crystal, very-high-resolution SANS spectrometer which has been used primarily to study vortex lattices in superconductors; (6) a four-circle diffractometer for crystallographic studies; (7) a more limited triple-axis unit with a fixed incident energy of 14.7 meV; and (8) a time-of-flight correlation chopper spectrometer. The latter has been equipped recently with a system of ultrasonically pulsed silicon crystals to monochromatize and pulse the neutron beam incident on the sample.

A new two-dimensional detector has been developed; it utilizes a 12-in.-diam neutron-sensitive LiF–ZnS phosphor, an image intensifier, and a television camera system. This detector has been extremely useful in the observation of diffuse scattering, superlattice formation, and powder patterns, as well as crystal characterization, all in real time (less than a second). The system also has image storing capabilities.

Some of the auxiliary equipment includes furnaces, closed-cycle refrigerators, helium-four cryostats, a helium-three cryostat, a superconducting magnet, and a helium-three–helium-four dilution refrigerator with a split-coil superconducting magnet, which is capable of reaching 7 mK and a field of 5 T.

For additional information contact H. A. Mook, Solid State Division, Oak Ridge National Laboratory, Oak Ridge, TN 37830.

C. Research reactor facility (MURR), University of Missouri, Columbia, MO

The University of Missouri operates a 10-MW reactor as a neutron and gamma radiation source for condensed matter research. Interested parties from outside the University are encouraged to make use of the facility through cooperative experiments with members of the staff, or through the Reactor Sharing Program, supported by the Department of Energy. At MURR there are facilities to conduct experiments in at least four areas related to condensed matter physics research. (1) For neutron scattering, two triple-axis spectrometers are available to measure dispersion relations; two single-crystal diffractometers and one powder diffractometer are available to measure atomic and magnetic ordering in condensed matter systems; one small-angle neutron scattering spectrometer is available for polymer and molecular biological studies; a neutron interferometer can be used for special experiments. (2) For gamma scattering, three unique instruments are available: MUGS, which is a gamma-ray diffractometer for structure studies; QUEGS, which is a gamma diffractometer with Mossbauer energy analysis for quasielastic gamma measurements; and COGS, which is a Compton spectrometer now available for measuring momentum distribution of electrons. (3) Trace element analysis can be done by instrumental, radiochemical, and prompt neutron activation; it allows the characterization of elements in condensed matter samples. (3) Analyses of deep levels in the band gap of semiconductors can be made by using deep-level transient spectroscopy, current transient spectroscopy, and the newly developed charge transient spectroscopy, which allows 10^{10} deep levels per cubic centimeter to be detected.

For additional information contact R. M. Brugger, Director, Research Reactor Facility, Research Park, Columbia, MO 65211.

D. NBS research reactor, National Bureau of Standards, Gaithersburg, MD

The NBS research reactor is expected to double its power to 20 MW by the end of 1983. In March of 1983 it had 25 experimental facilities installed for materials reseach, activation analysis, radiation standards, and nuclear physics. Ten of the horizontal beam ports are dedicated to condensed matter science, with a wide variety of neutron scattering instruments installed. Special features include: (1) a three-axis spectrometer with two low background analyzer systems to allow measurements ranging from soft modes and spin-wave excitations in solids (as low as 1.0 meV) to the spectroscopy of low levels of hydrogen and molecular species in metals and catalysts (30–300 meV); (2) a multidetector high-resolution diffractometer used to study complex structures by powder diffraction, e.g., magnetic intermetallic compounds, catalysts, and ionic conductors; (3) a biological diffraction station used to study the structure of proteins; (4) a depth profiling facility for the nondestructive determination of density profiles of selected elements near surfaces; and (5) a small-angle neutron scattering facility with continuously variable wavelengths from 4 to 10 Å, a wave vector transfer range from 0.003 to 1.0 $\mathrm{\AA}^{-1}$, and on-line color graphics for the study of microstructure in metals, polymers, and biological materials.

For additional information contact J. J. Rush or J. M. Rowe, National Bureau of Standards, Washington, DC 20234.

E. National Center for Small-Angle Scattering Research, Oak Ridge National Laboratory, Oak Ridge, TN

The National Center for Small-Angle Scattering Research is a user-dedicated facility supported by the National Science Foundation and the Department of Energy under an interagency agreement. The two main instruments available to users are the NSF-supported 30-m small-angle neutron scattering facility (SANS) and the DOE-supported 10-m small-angle x-ray scattering camera (SAXS). These instruments are intended to provide state-of-the-art capability for investigating condensed matter structures in a range from a few tens up to several hundreds of angstroms. They are intended to serve the needs of scientists in the areas of biology, polymer science, chemistry, metallurgy and materials science, and solid-state physics.

For additional information contact W. C. Koehler, Director, or M. Gillespie, Secretary, NCSASR, Oak Ridge National Laboratory, Oak Ridge, TN 37830.

F. Intense Pulsed Neutron Source, Argonne National Laboratory, Argonne, IL

The Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (ANL) is the most intense neutron spallation source now operating in the world. Protons from a 50-MeV linear accelerator and a 500-MeV rapid cycling synchrotron are delivered to a uranium target at a frequency of 30 Hz to produce neutrons. In the first year of operation 3370 h of research time were available. The peak thermal flux of IPNS is 3×10^{14} n/s cm^2.

The instrument package at IPNS has been designed with particular attention to the rich epithermal spectrum of neutrons present in such a spallation source. For example at 500-MeV IPNS has an effective flux approximately 10 times greater than the hot source at the Institute Laue Langevin (Grenoble, France).

The instruments for elastic or total scattering consist of two powder diffractometers (one a general purpose diffractometer and one a special environment diffractometer) which have excelled at high-resolution work and have also proven useful for studying amorphous systems. A single-crystal diffractometer is based on the Laue technique with a position-sensitive two-dimensional (30×30 cm) detector. A small-angle diffractometer also includes a position-sensitive detector, and is used for both metallurgical and biological problems. Of particular interest is the possibility of using epithermal neutrons in resonance small-angle scattering on biological molecules.

For inelastic scattering the crystal-analyzer spectrometer is particularly well suited to examine dispersionless high-energy vibrational modes. Two chopper spectrometers have proved exceptionally versatile in a variety of problems involving measurements of inelastic cross sections.

A new instrument, an electron-volt spectrometer, is under construction.

In the first year of operation approximately 120 experiments were performed at IPNS in the 3370 h of research time that was available. People from 23 universities, 5 industrial laboratories, 5 U. S. National Laboratories, and 8 foreign institutions were involved.

For additional information contact T. G. Worlton, Scientific Secretary, IPNS, Argonne National Laboratory, Argonne, IL 60349.

G. Weapons Neutron Research/Proton Storage Rings (WNR/PSR) Facility, Los Alamos, NM

The WNR is already operational as a high-intensity spallation neutron source. The user program was scheduled to begin in September 1983. Two-thirds of the neutron scattering beam time will be allocated for outside use and one-third reserved for in-house use. The first two user instruments will be the Be–BeO filter difference spectrometer (especially suited for chemical spectroscopy, and for studies of density of vibrational states and of optical modes of solids), and the single-crystal diffractometer (wavelength-resolved Laue camera). New instruments will be added to the user program as they become available and reach maturity. The tentative list of WNR instruments with their year of first operation and projected year for entry into the user program is: (1) filter-difference spectrometer (1980, 1983); (2) single-crystal diffractometer (1980, 1983); (3) liquids, amorphous, and special environment diffractometer (1980, 1984); (4) powder diffractometer (1980, 1984); (5) constant wave-vector-change spectrometer (1983,1985); (6) electron-volt spectrometer (1980,1985); (7) chopper spectrometer (1984,1986); and (8) small-angle diffractometer (1986,1987).

Some highlights of the research program to date include: (1) model-independent determination of the hydrogen–hydrogen pair correlation function in liquid water; (2) determination of the structure of the first molecular hydrogen complex; (3) observation of a new correlation of hydrogen bond vibrational frequencies with bond length for very short hydrogen bond; (4) development of the nuclear-resonance filter-difference method for electron-volt spectroscopy; and (5) observation of hydrogen momentum distributions in hydrides and water by scattering in the impulse approximation.

For additional information contact R. N. Silver, Group P-S, MS-H805, Los Alamos National Laboratory, P. O. Box 1663, Los Alamos, NM 87545.

II. SYNCHROTRON RADIATION SOURCES

The five synchrotron radiation sources in the United States are described here. The newest entrant in the field, the NSLS, is still in the process of coming into full-scale operation, and the others are still undergoing enlargement and improvement. This is a rapidly growing area of research throughout the industrialized world.

Figure 1 is an aerial view of the Stanford Synchrotron Radiation Laboratory.

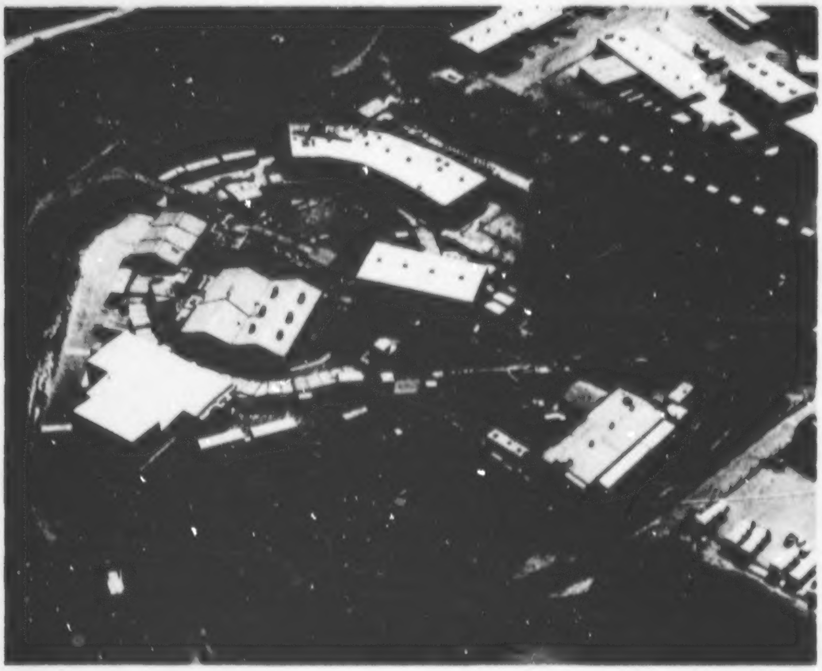

FIG. 1. An aerial view of the Stanford Synchrotron Radiation Laboratory.

A. Standford Synchrotron Research Laboratory (SSRL), Palo Alto, CA

SSRL is a national facility for the utilization of synchrotron radiation in biology, physics, materials science, medical science, and other disciplines. It is funded by the Department of Energy. The radiation comes from the storage ring, SPEAR, a facility within the Stanford Linear Accelerator (SLAC) built originally for high-energy physics research.

SPEAR is dedicated to the production of synchrotron radiation half of its operating time. During this time high currents of electrons, up to 100 mA are stored at high energies (3–3.5 GeV). The other half of the time the ring operates for high-energy physics research purposes to produce colliding beams of electrons and positrons. The ring is in operation between 8 and 9 months out of each year.

In addition to scientific research the Laboratory had a commitment to the development of advanced insertion devices for the enhancement of synchrotron radiation and the development of state-of-the-art instrumentation for the utilization of synchrotron radiation.

At present SSRL has 16 experimental stations on five beam lines covering the spectrum from 6 to 40 000 eV. A wide variety of experimental equipment is available for the user, and there are no charges either for the use of the beam or of the facility-owned support equipment. Both a 54-pole wiggler line and an undulator beam line serving three experimental stations are being developed; they will cover a range from 10 to 1000 eV.

SSRL is currently used by approximately 550 scientists from 124 different institutions, including universities, private corporations, and government laboratories.

As of March 1983 a total of 797 proposals had been received since March 1974, out of which 190 were active. A typical project involves four to eight scientists, including graduate students and post doctorals. Approximately 100 graduate students from 15 different universities work at SSRL each year. Over 200 publications based on research conducted at SSRL appear in journals each year.

For additional information contact A. Bienenstock, Director, Stanford Synchrotron Radiation Laboratory, P. O. Box 4349, Bin 69, Standford, CA 94305.

B. Cornell High Energy Synchrotron Source (CHESS), Cornell University, Ithaca, NY

CHESS, the Cornell High Energy Synchrotron Source, is a national laboratory which provides six x-ray experimental stations. X rays come from an 8-GeV electron storage ring (CESR). Monochromatic tunable photon beams from 4 to 100 keV are available. A six-pole 1.8-T wiggler provides a particularly intense spectrum with a critical energy in excess of 30 keV. The CHESS x-ray spectrum has a unique time structure—pulses come at 2.56 μs intervals with a pulse width of 0.13 ns.

Two stations provide white-beam capabilities, particularly useful for topography, high-pressure studies, and experiments that contain their own unique monochromators. A four-axis Huber diffractometer and two Picker diffractometers are available for diffraction physics experiments. Two complete EXAFS stations with data-acquisition software and off-line analysis packages are provided.

CHESS is supported by the National Science Foundation and currently provides experimental capabilities for approximately 100 active research proposals from all over the U. S. A.

For additional information contact Nancy Miller, Proposal Administrator at CHESS, Wilson Laboratory, Cornell University, Ithaca, NY 14853.

C. National Synchrotron Light Source, Brookhaven National Laboratory, Upton, NY

The National Synchrotron Light Source (NSLS) is designed to provide the world's brightest continuous source of x rays and UV radiation. It is also the first x-ray facility in the United States dedicated for use as a synchrotron light source. It consists of two electron storage rings, one at 750 MeV for the production of vacuum ultraviolet (VUV) radiation, and one at 2.5 GeV for the production of x rays. In mid-1983 the VUV storage ring was in reliable operation with currents up to 300 mA and a lifetime of 2 h at 100 mA. The x-ray ring had stored beam, and initial operation for experimenters was expected during the latter part of 1983.

The VUV ring has 16 ports for VUV and IR research. It incorporates a unique free-electron laser designed to be a narrowband (relative bandwidth of 10^{-6}), continuously tunable (2000–4000 Å) UV source with average power in the range from one to several watts. The free-electron laser undulator can be used during routine storage ring operations to produce intense radiation between 100 and 2000 Å. The x-ray storage ring has 28 ports. Each of the 16 VUV and 28 x-ray ports is divided into two or three individual beam lines.

Under construction are several wiggler and undulator magnets which will significantly increase the photon energy and brightness.

The facility has a wide range of research equipment for basic and applied studies in condensed matter, surface science, photochemistry and photophysics, lithography, crystallography, small-angle scattering, metallurgy, x-ray microscopy, etc.

The NSLS is a national user facility, available without charge to university, industrial, national laboratory, and government users. There are several modes of use of the experimental facilities. A large number of beam lines have been designed and constructed by 27 participating research teams (PRTs). The PRTs are, for most part, user groups from outside Brookhaven National Laboratory with large, long-range programs which have been approved by the NSLS Program Advisory Committee. The PRTs are given priority for up to 75% of the operational time of their beam lines. General users will be scheduled for both PRT beam lines and for lines built by NSLS for the community in general.

For additional information contact M. Blume, Chairman, National Synchrotron Light Source, Brookhaven National Laboratory, Upton, NY 11973.

D. Synchrotron Radiation Center, University of Wisconsin, Stoughton, WI

The Synchrotron Radiation Center (SRC) of the University of Wisconsin operates the Tantalus 240-MeV electron storage ring and is bringing on line the Aladdin 1-GeV ring. When Aladdin is in operation, it will have 35 equivalent bending magnet source points and one inverse Compton scattering source point. Ten beam lines will be fully instrumented and maintained by the SRC. Monochromators will span the spectral range from about 4 to 1200 eV; there are plans to develop a soft x-ray crystal monochromator to extend the range to 4000 eV. Beam lines and monochromators will be available to users on a request-for-time basis. Since no single monochromator is able to span the entire range made available by Aladdin, requests for beam time should be specific on the choice of monochromator or the spectral range needed.

In addition to the ten facility beam lines, thirteen beam lines are being implemented by groups of users, called participating research teams (PRTs), each with its own specific purpose. Access to these instruments will be possible through negotiations involving the SRC director and the PRT involved.

When completed, Aladdin will have 23 monochromators operating on 21 beam lines, including five high-flux Seya-Namioka's (5–50 eV), three normal-incidence monochromators (including a 6-m ultrahigh resolution instrument), five toroidal grating monochromators (6–180, 225, and 700 eV), three high-resolution grasshoppers (20–1,000 eV), five high-resolution extended range grasshoppers (5–1500 eV), and a soft x-ray emission spectrograph. In addition, one x-ray crystal/grating (800–4000 eV) instrument has been authorized and a second is proposed.

Special facilities planned include an inverse Compton scattering line; a facility to handle transuranic, radioactive materials; soft x-ray lithography; ultraviolet and soft x-ray photoelectron spectroscopy systems with angle-integrated and angle-resolving capabilities; circular and magnetic circular dichroism; reflectance and absorption spectroscopies; and photon stimulated desorption.

Aladdin will operate—and Tantalus does operate—as a dedicated synchrotron source on a five day per week schedule with 48.5 h of beam time available for research. As with other national facilities, the user is responsible for the operation and the safety of his own instrumenation. The operation of the laboratory facilities is overseen by the SRC staff. The Physical Sciences Laboratory (PSL) of the University of Wisconsin provides the necessary support for the users, including computer capabilities (a VAX 11/780), purchasing services, mechanical and electrical engineering services, an outstanding machine shop, a library, and a stockroom. Housing is available at the PSL Guest House.

For additional information contact E. M. Rowe, Director, Synchrotron Radiation Center, 3725 Schneider Drive, Route 4, Stoughton, WI 53589.

E. NBS Synchrotron Radiation Facility, National Bureau of Standards, Gaithersburg, MD

The Synchrotron Ultraviolet Radiation Facility (SURF-II) at the National Bureau of Standards is a 280-MeV electron storage ring used as a dedicated light source in two areas of science: radiometry and experimental physics. Since the facilities for each of these two uses are for the most part independent, they are described separately.

The radiometric facilities fall into two classes: calibration and radiometric standards. SURF-II is an ideal light source for calibration since it is a single-magnet accelerator with a perfectly circular orbit. This feature allows the spectral distribution from the ring to be calculated with an accuracy of 2%. The calibration beam line consists of a white light port with accurate baffling to ensure a well-defined light beam. The beam light is equipped with a two-axis, two-transition gimbal on which a vacuum chamber or windowed instrument can be mounted. After an instrument is mounted, it is rotated about its entrance slit so that the light beam is scanned over its entire optical surface. For instruments which do not have their own vacuum envelope, e.g., rocket-borne or space-shuttle spectrometers, the beam line can be attached to a large vacuum chamber ($4 \times 4 \times 8$ ft) capable of attaining 10^{-8} Torr. A two-axis goniometer in the chamber again allows the mounted instrument to be rotated and the entire optical surface to be calibrated.

The radiometric standards beam line is used primarily for the calibration of photodiodes which are sold by NBS. It consists of a toroidal grating monochromator to disperse the light, a double ionization chamber to measure absolute photon intensity, and the diode chamber. Each diode is calibrated as a function of photon energy and is available as a secondary photometric standard. The calibration covers the photon energy range from 5 to 100 eV.

The facilities for experimental physics consist of three beam lines equipped with four monochromators. The first instrument is a high-flux, normal-incidence monochromator equipped with a differential pumping chamber to allow windowless gas-phase experiments. A pressure of 10^{-4} Torr can be maintained in the experimental chamber while the ring is operating. The spectral range is from 350 to 2000 Å, with a resolution of 0.05 Å. The maximum intensity is 10^{11} photons per second out of the exit slit.

The second instrument is a grazing-incidence, Rowland circle monochromator with an experimental chamber designed for reflectivity measurements. It covers the range from 80 to 800 Å, with a resolution of 0.15 Å. A gimbal in the experimental chamber allows a channeltron electron multiplier detector to be scanned about the sample.

The third monochromator has a range of 165 to 500 Å, with a resolution of 1 Å and an output of 10^{9} photons per second on the sample in a 2-mm-diam spot. A reentrant arrangement allows the sample to be placed within 2 cm of the slit. The experimental chamber contains a cylindrical mirror analyzer for surface-science studies. Both electron and ion emission from well-characterized surfaces can be studied.

The fourth monochromator is similar to the third one, but with a spectral range from 300 to 1000 Å. There is no permanent experimental chamber attached to it.

All these instruments are equipped with dedicated computers for experimental control and data acquisition.

Several monochromators are under construction. One is for a new radiometry facility which will also be available for experimentation. The second is a new high-flux, ultrahigh-vacuum monochromator to replace the surface-science facility. This instrument was being installed during the fall of 1983. Finally, a normal incidence monochromator with a resolving power of 10^{5} is scheduled to be in operation by the summer of 1984.

For additional information contact R. P. Madden, or D. L. Ederer, National Bureau of Standards, Washington, DC 20234.

III. FACILITIES FOR MICROANALYSIS, MICROFABRICATION, AND SURFACE STUDIES

The five facilities described in this section provide a great variety of sophisticated devices for probing, characterizing, and altering the structures of materials, and for preparing new materials and new structures. Surfaces and microstructures command a large share of the effort. It is worth noting that these facilities allow numerous powerful techniques to be brought to bear simultaneously on a single problem.

Figure 2 shows a small section of an array of resonant elements—dipole openings in a gold film deposited on calcium fluoride—fabricated at NRRFSS (see Sec. A below). The array acts as a band rejection transmission filter in the mid-infrared (7–9μ). The primary resonant frequency is one-hundred times higher than any previously reported.

A. National Research and Resource Facility for Submicron Structures, Cornell University, Ithaca, NY

In 1977 the National Science Foundation established a National Research and Resource Facility for Submicron Structure (NRRFSS) to help advance submicron science and technology. The specific objectives of NRRFSS are: (1) to promote and carry out research to advance the art of submicron fabrication technology, and to train scientists and engineers in this field; (2) to provide a resource primarily for use by the university community to fabricate advanced devices or research structures which require submicron dimensions; (3) to stimulate innovative research outside the electrical engineering device community which will shed light on fundamental physics or materials problems limiting submicron technology; and (4) to keep the technical community informed on progress at the Facility.

Microfabrication research at NRRFSS involves about one hundred Cornell graduate students representing about eight departments and thirty-five faculty members. In addi-

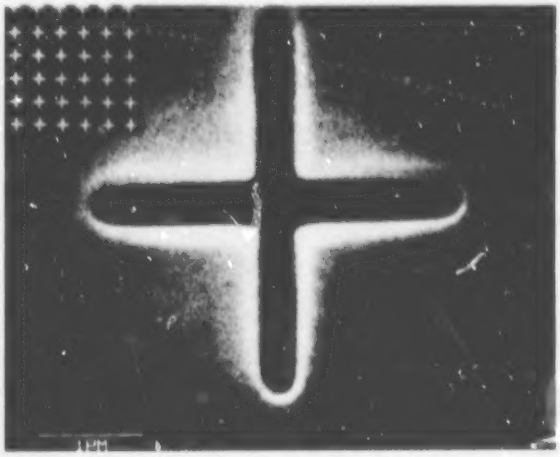

FIG. 2. A small section of an array of resonant elements fabricated at NRRFSS. Enlargements of one element, 3 μ long, also shown.

tion there are currently about thirty approved user projects outside Cornell. The Cornell research includes both facility development research and user research. The facility development research emphasizes enhancement of equipment and techniques in advanced lithography and dry pattern transfer processing as well as thin-film growth, deposition, and modification and, to a lesser extent advanced device technologies and thin-film electrical, chemical, and structural analysis. Both facility development research and user research projects are initiated by a proposal review process.

For additional information contact E. D. Wolf or R. A. Brown, NRRFSS, Knight Laboratory, Cornell University, Ithaca, NY 14853.

B. The Center for Microanalysis of Materials, University of Illinois, Urbana, IL

It is not possible for an individual group to support equipment and maintain an interest in all of the techniques of microanalysis. The result is that, in general, a research group specializes in a particular characterization technique and tailors its research to it. The University of Illinois has adopted a different approach: instrumentation for microcharacterization of materials has been gathered into the Center for Microanalysis of Materials that operates as a facility for all of the materials research programs on campus and many collaborative research programs with other universities and laboratories.

The Center has transmission electron microscopes, scanning electron microscopes, a scanning transmission electron microscope, electron microprobes, scanning Auger microscopes, secondary ion microprobes, an x-ray photoelectron spectroscopy unit, rotating and fixed anode x-ray sources fitted with instrumentation for EXAFS, topography, small-angle scattering and all standard x-ray methods, and an accelerator for backscattering spectroscopies. Most of these instruments are modern commercial machines fitted with a wide range of accessories and instrumentation. In addition the Center has extensive facilities for specimen preparation. The Center is operated by a staff of about a dozen professionals/academics who guide and collaborate in research, maintain the equipment, and give instruction for its use.

More than a hundred faculty members on the University of Illinois campus carry out research in materials science. The Center for Microanalysis of Materials provides them with the unique opportunity to use almost any microanalytical technique, or combination of techniques, to characterize their samples.

A flexible program of interaction with other institutions is also maintained. For additional information contact J. A. Eades, Materials Research Laboratory, University of Illinois, 104 S. Goodwin, Urbana IL, 61801.

C. ORNL Surface Modification and Characterization Collaborative Research Center, Oak Ridge, TN

The Oak Ridge National Laboratory Surface Modification and Characterization Collaborative Research Center (SMAC) is a facility for cooperative research involving university and industrial scientists working with ORNL personnel on problems of mutual interest. The goal of the center is to provide and maintain advanced processing and characterization techniques for *in situ* alteration and analysis of near-surface properties of a wide range of materials.

The materials processing capabilities of the Center feature ion implantation doping, ion beam and laser mixing, and pulsed-laser processing. These are all nonequilibrium processing techniques capable of achieving new and often unique materials alterations not possible with equilibrium processing methods. The *in situ* materials characterization capabilities emphasize ion scattering and nuclear reaction analysis, ion channeling, surface analysis techniques (LEED, Auger, etc.), and other property measurements such as electrical resistivity and optical reflectivity.

The SMAC facility is equipped with beam lines from positive-ion analysis accelerators and a high-current ion implantation accelerator integrated into common ultra-high-vacuum chambers (10^{-10} Torr) which contain surface analysis instruments, solid-state detectors, and UHVgoniometers and sample holders, as well as optical windows which allow *in situ* laser processing. With these facilities it is possible to alter materials properties in UHV by ion beam and laser processing at sample temperatures from 4 to 1,300 K, and to analyze the materials in place. The ion accelerators include a 2.5-MeV Van de Graaf, a 200-keV high-current implantation accelerator, and a 1.7-MeV tandem accelerator, with both duoplasmatron and heavy-ion sources. The latter is scheduled for operation in 1984. A wide range of high-powered lasers is available, including ruby, Nd:Yag, and KrF lasers (15×10^{-9} s pulse duration time); a mode-locked Nd:Yag laser (30×10^{-12} s pulse duration time); and a cw Ar ion laser. With these laser sources it is possible to achieve heating and cooling rates that vary from approximately 10^6 to approximately 10^{12} °C per second in the near-surface region.

Facilities in the Center are being expanded to accommodate more users. For additional information contact B. R. Appleton, Solid State Division, ORNL, Oak Ridge, TN 37830.

D. SHaRE Program, Oak Ridge National Laboratory, Oak Ridge, TN

The SHaRE Program is a collaborative research venture in materials science between the research staff of ORNL and the research staff at both universities and industrial laboratories. Managed by Oak Ridge Associated Universities, its purpose is twofold: (1) to permit ORNL research staff members to carry out additional research relevant to the Department of Energy programs that would not ordinarily be possible; and (2) to make available to university staff and industrial researchers sophisticated research equipment at ORNL which is not available in their home institutions.

All research sponsored at ORNL under the SHaRE program is collaborative, with at least one ORNL staff member and one senior researcher from the outside institution having joint responsibility for successful completion of each project and for publication of the work.

From its inception in late 1978, the SHaRE program has concentrated on the application of advanced microanalytical techniques to research areas in materials science. Centered in the Metals and Ceramics Division, the facilities used under the SHaRE program include the analytical electron microscopes, the high-voltage electron microscope facility, the Auger electron spectrometry/surface microanalytical apparatus, the Van de Graaf nuclear backscattering equipment, and the computer facilities. Once a project is established as a collaborative SHaRE program, there is no charge for the use of the facilities. Access to the program requires submission of a proposal which involves an interested ONRL collaborator.

For additional information contact E. A. Kenik, Metals and Ceramics Division, Oak Ridge National Laboratory, P. O. Box X, Oak Ridge, TN 37830.

E. Regional instrumentation Facility (CRISS), Montana State University, Bozeman, MT

The regional Instrumentation Facility at the Montana State University Physics Department (CRISS: Center for Research in Surface Science and Submicron Analysis) is devoted principally to basic and applied research in surface physics and chemistry. The main instrumentation includes: (1) a scanning Auger microprobe; (2) a high-resolution electron-energy-loss spectrometer with double-pass monochromator and analyzer; and (3) an ESCA system with Al/Mg double-anode x-ray head and hemispherical analyzer; the ESCA system is housed in the same vacuum as (2).

A singular advantage of this arrangement is the possibility of doing ELS and ESCA experiments in conjunction. The ESCA analyzer can do ion scattering spectroscopy in conjunction with the ion gun. The chamber supports a SIMS add-on based on a quadrupole mass analyzer. A third vacuum chamber supports a low-resolution (5-μ beam size) scanning Auger spectrometer and a He-discharge lamp for Ultraviolet Photoemission Spectroscopy. The laboratory also has the usual support facilities.

Although the advice and assistance of the staff are available to whatever extent necessary for effective execution of the experiments, the laboratory is operated primarily as a user facility, and the users are expected to plan and execute their own experiments, devoting the necessary time (from 1 to 3 days) to learn the operation of the equipment. The user's stay at the facility is generally from one to three weeks.

The staff includes a director, two staff scientists, a technician, and an administrative assistant. For additional information contact G. J. Lapeyre, Physics Department, Montana State University, Bozeman, MT 59717.

IV. ELECTRON MICROSCOPES

High voltage and ultrahigh resolution in electron microscopy require large installations. The three installations described here provide advanced capabilities for users. An example of the work is shown in Fig. 3, which is a micro-

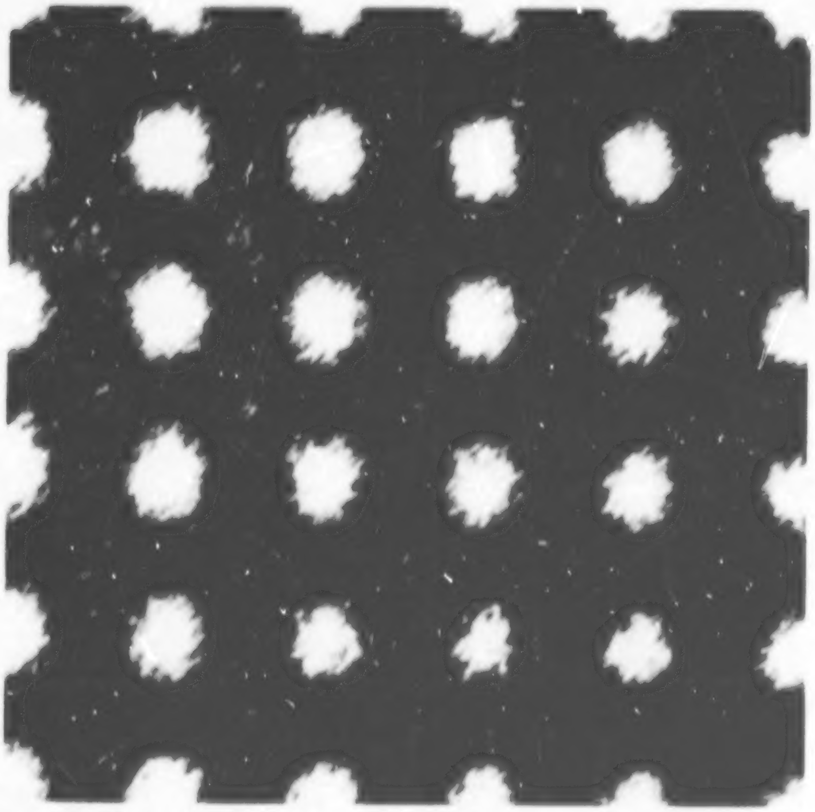

FIG. 3. Micrograph of zirconium dioxide with atomic resolution, taken on the JEM ARM-1000 at the National Center for Electron Microscopy.

graph of zirconium dioxide with atomic resolution. All atomic positions in a (0 0 1) projection are shown. The photograph was taken on the JEM ARM-1000 at the National Center for Electron Microscopy.

A. Facility for High Resolution Microscopy, Arizona State University, Tempe, AZ

The Facility for High Resolution Microscopy in the Center for Solid State Science at the Arizona State University is supported by the National Science Foundation and the State of Arizona. The goals of the Facility are to advance the methods and instrumentation of electron microscopy; to apply new research methods to the structural analysis of solids, particularly in the areas of materials science, solid-state physics, solid state chemistry, and geology; and to provide high-resolution research facilities for use of scientists and engineers from the solid-state science community at large. In addition, the Facility conducts topical research conferences and advanced electron microscopy schools each January.

The principal research topics of current interest are high-resolution imaging of surfaces and interfaces, electron-loss spectroscopy, microdiffraction, and energy dispersive x-ray spectroscopy. There are, at present, six electron microscopes at the facility, including two field-emission-source instruments (EM400/ST and HB-5) and a fixed-beam imaging instrument with 2.5-Å resolution. The field-emission-source instruments have been shown capable of high coherent microdiffraction from specimen areas as small as 5 Å, and microspectroscopy from areas about 10 Å in diameter. These experimental methods are being applied to an increasing number of intriguing problems, particularly in the areas of electronic materials, surfaces, and catalysts.

During the last year, more than twenty outside scientists conducted research at the Center with the assistance of an on-site support staff, and about forty on-site research programs made use of the Facility.

The topic of the January 1983 Research Conference at the Facility was High Resolution Imaging and Microanalysis of Surfaces. The conference topic for January 1984 is High Resolution Structural and Chemical Analysis of Boundaries and Interfaces.

For additional information contact the Director, Facility for High Resolution Electron Microscopy, Center for Solid State Science, Arizona State University, Tempe, AZ 85287.

B. National Center for Electron Microscopy, Lawrence Berkeley Laboratory, Berkeley, CA

The National Center for Electron Microscopy (NCEM) is primarily a high-voltage electron microscope facility with instrumentation designed for ultrahigh resolution or dynamic *in situ* imaging of materials. The Center is supported by the U. S. Department of Energy, and its instruments have been designated as user facilities.

Among the unique microscopes in the NCEM is a Kratos EM-1500, the only instrument in the U. S. which provides accelerating voltages in the 1200–1500-kV range. It features both a top-entry goniometer stage for high-resolution work and a side-entry stage for dynamic *in situ* and environmental cell studies. Depending upon the choice of specimen holder, the sample can be viewed over a plus or minus 45 deg tilt angle, at temperatures ranging from ambient to 850 °C and with various gaseous environments up to 1 atm pressure. Dynamic events can also be recorded on video tape. The operating pressure in the optical column can be brought to 10^{-7} Torr and the microscope has demonstrated a point-to-point resolution of about 3 Å.

A second instrument is the JEM ARM-1000, the only instrument of its kind in the world, providing a point-to-point resolution of 1.7 Å or better over all operating voltages up to 1000 kV. It has a top-entry goniometer stage with 45 deg biaxial tilting and height adjustment which, in addition to variable focal length, enables convergent beam electron diffraction patterns to be taken from the same specimen areas imaged in high resolution. Operating pressures are in the 10^{-5}-Torr range. The microscope makes extensive use of microprocessor control for precise operation, and has very high brightness (10^8 A/cm^2 ster) due to its lanthanum hexaboride filament design.

Other microscopes within the NCEM include a JEOL JEM 200CK with an ultra-high-resolution goniometer and a Hitachi HU-650 high-voltage electron microscope with hot stage and environmental cell. By September 1983 a new building addition should have been completed to house the remainder of the NCEM support equipment, including wet and dry specimen preparation laboratories, optical diffractometer, image analysis and processing hardware, and an on-site minicomputer-based image simulation laboratory to assist with micrograph interpretation.

Beam time of the NCEM microscopes is allocated after review and acceptance of research proposals submitted in advance. In accordance with Department of Energy policy, as long as the proposed work is of documented programmatic interest to the Department and the results are published in the open literature, there is no charge for use of the NCEM microscopes.

For additional information contact G. Thomas, Scientific Division, or K. H. Westmacott, Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720.

C. HVEM-Tandem-Accelerator National User Facility at Argonne National Laboratory, Argonne, IL

The High Voltage Electron Microscope (HVEM)-Tandem Facility is a unique national research facility. It is supported by the U. S. Department of Energy and is available to scientists from industry, universities, and other national laboratories, after approval of submitted research proposals. The facility is operated by the Materials Science and Technology Division of ANL and provides a unique combination of capabilities for high-voltage electron microscopy, ion implantation/bombardment, and ion beam analysis. A number of side-entry stages permits *in situ* experiments in the temperature range from 10 to 1300 K *in vacuo*, and from ambient to 1300 K in noncorrosive gaseous atmospheres. Straining stages are available for deformation and fracture studies over a wide range of experimental conditions. The

HVEM/ion beam interface permits direct observation of the effects of electron and ion bombardment on materials in the microscope. The ion beam interface may be used with either a 300-kV ion accelerator or the 2-MV tandem ion accelerator. Calibrated dosimetry systems are available for both ion and electron beams.

Prime-time usage of the facility is divided approximately equally between ANL and non-ANL scientists. The facility staff is available during one or two shifts a day to instruct experimenters in the use of the equipment, and in some intances to participate in experimental programs. In general researchers are expected to become competent to operate the equipment. A course of lectures on high-voltage microscopy supplemented by lecture notes is available on video tape.

When not scheduled for use with the HVEM the 2-MV Tandem and the 300-kV accelerators are used separately from the microscope by the ANL staff. Outside users wishing to use the accelerators alone are requested to collaborate with the appropriate group of the Materials Science and Technology Division of ANL.

For additional information contact the Facility Secretary, Sheryl Ruffatto, Building 212, Argonne National Laboratory, Argonne, IL 60439.

V. OTHER FACILITIES

This section lists several facilities that do not fit in the foregoing categories. They are the Francis Bitter National Magnet Laboratory, which provides ultrahigh magnetic fields of various kinds; the Los Alamos Equation of State Library, which provides the latest information on matter under extremes of pressure and temperature; and the Combustion Research Facility, which provides powerful new capabilities for the study of combustion in engines and other systems.

A. The Francis Bitter National Magnet Laboratory, M.I.T., Cambridge, MA

The Francis Bitter National Magnet Laboratory is the largest facility in the world for generation of intense continuous magnetic fields. The Laboratory traces its origin to the work of Prof. Francis Bitter, who pioneered electromagnetic technology in the 1930's; it was organized as a national laboratory in 1960 and started its operation at the present site in 1963. The National Science Foundation has been sponsoring the Laboratory's operation since 1970.

The Magnet Laboratory's facilities are available to users free of charge. A variety of high-field magnets are provided, together with cryogenic measurement and data processing equipment. Experienced support staff is also available on a full-time basis to assist visitors with all aspects of their experiments. Research staff at the Laboratory can be consulted about problems in specialized areas.

The Laboratory features almost two dozen water-cooled (Bitter) magnets in five bore diameters from 3.3 to 24.8 cm, with fields as high as 25 T in a 5.4-cm bore and 30 T in a 3.3-cm bore.

All fields are calibrated to 0.1% and are repeatable and stable to 0.05% short term, and 0.1% long term. Time stability of a few parts in 100 000 can be obtained with a localized feedback system. This system makes it possible, for example, to do nuclear-magnetic-resonance experiments in spatially uniform fields and to reduce eddy-current heating in low-temperature experiments. At the other extreme, modulation fields of up to 0.5 T peak-to-peak at 7.5 Hz can be generated for use with ac signal processing in, for example, quantum oscillatory experiments. The dc fields can be swept continuously from zero to maximum in as little as 1 min or as much as 2 h. Field setting, sweep, and modulation are all under local control by the user.

Two new sets of magnets should become available soon: (1) a pulsed-field facility which offers fields up to 45 T with 10-ms duration in a 1-cm bore at 4.2 K (1.5-cm bore at 77 K); (2) a superconducting magnet with a 20-min sweep to a 15-T field and a 5-cm room temperature access.

Users have available to them a broad range of equipment and apparatus, including complete temperature control systems with a range from 1.5 to 300 K, helium-3 and dilution refrigerators, and a complete de Haas–van Alphen apparatus along with homogeneous fields up to 24 T.

There is a queue of approximately three months for reserved magnet time—which is assigned in blocks of 15 to 30 h, depending on the power required. First-time users, however, can usually be accommodated within several weeks, and all users have the option of requesting magnet time on a recurring, biweekly basis. There is a separate queue for the use of the hybrid magnets.

For additional information contact Larry Rubin, Francis Bitter National Magnet Laboratory, NW-1108, M. I. T., Cambridge, MA 02139.

B. The Los Alamos Equation-of-State Library (SESAME), Los Alamos National Laboratory, Los Alamos, NM

The SESAME Equation-of-State (EOS) Library is a standardized, computer-based library of tables of thermodynamic properties and FORTRAN subroutines developed and maintained by the Equation-of-State and Opacity Group of the Theoretical Division of Los Alamos National Laboratory.

The Library contains data for about 70 materials, including metals, minerals, polymers, mixtures, etc., as well as simpler atomic and molecular species. The Library is being offered to all interested users free of charge.

The thermodynamic data stored in the Library include tables of pressure P and energy E (and also, in some cases, of Helmholtz free energy A), each as a function of density and temperature. Besides total P, E, and A tables, in many cases separate tables of thermal, electronic, and ionic (including zero point) contributions to P, E, and A are available. The SESAME EOS Library also has opacity data with a low-temperature limit of about 1 eV.

For further information on the SESAME EOS Library, write to SESAME Library, T-4, MS B925, Los Alamos National Laboratory, Los Alamos, NM 87545. Users interested in the opacity data should contact A. L. Merts or M. F. Argo, T-4, MS B212, Los Alamos National Laboratory, Los Alamos, NM 87545.

C. Combustion Research Facility, Sandia National Laboratories, Livermore, CA

The Combustion Research Facility (CRF) at Sandia National Laboratories in Livermore provides scientists an opportunity to study all phases of combustion science and technology. Researchers from universities, industry, and other government laboratories are encouraged to use the many laboratory and computer facilities, and to collaborate with resident scientists studying the basic chemistry and fluid mechanics of flames, as well as combustion phenomena occurring in devices such an engines and coal combustors. Central to nearly all CRF research is the incorporation of the most advanced laser-based techniques, many of which are being developed at the facility.

One part of this program is supported by the Division of Materials Sciences, Office of Basic Energy Sciences, U. S. Department of Energy, to develop a better understanding of the degradation of ceramic coatings and metallic alloys in the hot, corrosive, particulate-laden environments often present in combustion systems. Here, too, the application of the latest optical techniques has been strongly emphasized. Examples of such techniques, which are either in development or in use to study relevant problems, are:

(1) *In situ* surface Raman spectroscopy, which provides nonintrusive, real-time measurements of the chemical compositions and structural phases of corrosion layers building up on the surfaces of exposed materials.

(2) Raman microscopy, wherein Raman spectra are obtained with 1-μ resolution for the detailed characterization of polycrystalline or amorphous materials typical of most corrosion layers.

(3) Sputter-induced photon spectroscopy, in which optical emissions from excited atoms sputtered from surfaces provide high sensitivity for detecting trace species, including hydrogen, in insulating as well as conducting materials.

(4) Sputter-Raman spectroscopy, in which Raman spectroscopy is used to determine the depth profile of corrosion layers as material is removed by sputtering.

For additional information contact Walter Bauer, Department 8340, Sandia National Laboratories, Livermore, CA 94550.

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APPENDIX B

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PRESENTATIONS TO THE MAJOR MATERIALS FACILITIES COMMITTEE

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National Academy of Sciences, Washington, D.C.
February 26-27, 1984

Argonne National Laboratory: R. Kustom, G. Lander
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Synchrotron Radiation Panel

Molecular Biology Institute
University of California at Los Angeles
February 28, 1984

A 1.6 GeV Storage Ring: D. Shirley, D.Attwood, Lawrence Berkeley Laboratory

A 6 GeV Storage Ring*: A. Bienenstock, H. Wiedemann, Stanford Synchrotron Radiation Laboratory; D. Mills, B. Battermann, Cornell High Energy Synchrotron Source; M. Blume, S. Krinsky, Brookhaven National Laboratory; K. Kliewer, Y. Cho, Argonne National Laboratory

* The speakers shared the time describing science for a 6 GeV machine; each devoted a modest fraction of his presentation to site-specific plans.

Other Specialized Facilities Panel
National Academy of Sciences, Washington, D.C.
March 8, 1984

UV Laser Sources: G. Rosenblatt, Los Alamos National Laboratory
National Magnet Laboratory: P. Wolff, Massachusetts Institute of Technology
Muon Sources: R. H. Heffner, Los Alamos National Laboratory